Driven to the Future

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Driven to the Future

Carsickness in Autonomous Vehicles

Ouren X. Kuiper

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DRIVEN TO THE FUTURE:

CARSICKNESS IN AUTONOMOUS VEHICLES

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de Vrije Universiteit Amsterdam,
op gezag van de rector magnificus
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door

Ouren Xander Kuiper

geboren te Drunen

promotor: prof. dr. J.E. Bos

copromotor: dr. Cyriel Diels

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Chapter 1

Introduction

1.1 Introduction Outline

This thesis will explore various research questions surrounding carsickness in self-driving vehicles. In this introductory chapter, I will first lay out the relevant theoretical framework and examine why carsickness matters, in particular in autonomous vehicles. In the subsequent chapters I will discuss various findings, starting with a survey study on the extent of the occurrence of carsickness (chapter 2), followed by several experimental studies examining factors pertinent to carsickness. These include visual aspects (chapter 3 & 4), the use of simulators in carsickness research (chapter 5), the effect of predictably of motion on motion sickness (chapter 6), and a study how to potentially mitigate carsickness (chapter 7). In closing, I provide a general summary and discussion regarding the implications of these findings (chapter 8).

1.2a Theoretical background on motion sickness

Since ancient times, motion sickness has been a known problem affecting those exposed to physical motion. The word *nausea* originates from the Greek word ναύς, meaning ship (Horn, 2008). Humans exposed to waves aboard sea faring vessels were probably the first to experience the ill effects caused by external motion, although perhaps camel sickness might have been an even earlier contender (Huppert et al., 2017). Those afflicted by motion sickness experience a state of discomfort which can initially manifest in symptoms such as (cold) sweating, dizziness, headache, pallor, salivation, stomach awareness, burping, or apathy (Lackner, 2014). If exposure to provocative motion persists, these symptoms worsen and are subsequently followed by nausea, retching, eventually culminating in vomiting. When exposed to sufficient provocative motion, every healthy non-infant individual appears to be susceptible to motion sickness to some extent (Money, 1970; Balter et al., 2004). The only known exception to this are inner ear deficit patients, who were found to be the only passengers aboard a ship to be completely unaffected by the rough sea (James, 1882).This central dependence of the vestibular system (Cheung et al., 1991; Dai et al., 2017), suggests that motion sickness is in its core a vestibular issue.

The root cause of motion sickness is believed to be a discrepancy between actual and anticipated sensory signals. That is, sensory inputs (vestibular, proprioceptive, and visual signals) that are at odds with expected sensory patterns as derived from prior exposure to the spatial environment, lead to sickness. This theory was first outlined by Reason and Brand (1975), and named '*sensory rearrangement theory'*, later often referred to as '*sensory conflict theory*'. Do note, that this conflict is not necessarily between two senses, but rather between a current state against an expected sensory state. Nevertheless, a sensory conflict between two senses, such as a static visual scene but vestibular stimulation as when reading a book in a car, can be the decisive provocation leading to motion sickness. Central to the current theory on motion sickness, however, is that motion is not intrinsically nauseogenic due to a physiological effect, such as irritation of the vestibular organs (Irwin, 1881), but the result of a maladaptation, i.e. an error signal in internal regulation of posture and orientation. Reason and Brand's theory has been expanded upon by various authors, fully modelling the internal processes including the anticipation of sensory state following motor commands, referred to as an 'efference copy' (Oman, 1982, 1992; Bos & Bles, 2002; Bos et al., 2008). Specifically, the sensory conflict has been theorized to be reducible to an incongruence in estimating one's orientation to gravity (Bles et al., 1998; Bos & Bles 1998). A related but distinct theory is that of the postural instability theory (Riccio & Stoffregen, 1991; Stoffregen & Riccio, 1991). While also building on the framework of Reason and Brand (1975), it assumes that the quintessential aspect of motion sickness is a difficulty in keeping balance. i.e., an environment's external perturbations on person lead to motion sickness due to having to adapt to keep balance.

The vestibular organs are located in the inner ear. They consist of two parts: the otoliths, responsible for detection of linear motion and gravity, and the semi-circular canals, responsible for detection of rotational motion (Khan & Chang, 2013). Both are sensitive to acceleration, rather than to velocity. This is an important attribute of the vestibular system in the context of carsickness. While visually we are quite good at recognizing the magnitude of self-motion during constant speed, our vestibular system is unable to distinguish being stationary from traveling at a constant speed. Similar to how virtually no force is applied to us while the earth orbits the sun at extremely high velocity, Newton's 2^{nd} law explains that only an acceleration, i.e. change in velocity, applies force to the moving body and subsequently the vestibular sensors. On a smaller scale, that means that if you would travel in a straight line at a constant speed in a completely smooth train, elevator, or car, you would not be able to detect you were moving by vestibular cues alone. For a driving simulator, this is a useful given, as a highway drive at constant speed is generally only accompanied by limited accelerations, realizable by a moving base simulator. Visually, the suggestion of motion can, however, prove its own problem in terms of motion sickness, mainly due to vection, as will be discussed in chapters 4 and 5. These inherent limitations of our senses, i.e. their inability to always accurately discern the velocity and position of our body (Bos & Bles, 2002), necessitate a neural system to optimize locomotion and orientation in space, as will be discussed in the following section.

1.2b An internal model

The manner by which the various sensory inputs are internalized, subsequently used for balance and orientation, and even potentially lead to motion sickness, has been formalized into the following motion sickness theory (MST). This theory is an elaboration of the sensory conflict theory (Reason & Brand, 1975). First proposed by Oman (1982, 1990), it allows for a mathematical representation of the processes underling spatial orientation and motion sickness. It incorporates an internal representation of sensory and bodily states, such as an estimate of orientation in space. This estimate has also been referred to as "expectation", and lies at the basis of the conflict leading to motion sickness. Figure 1.1 shows a simplified model based on this theory, which will be further explained presently.

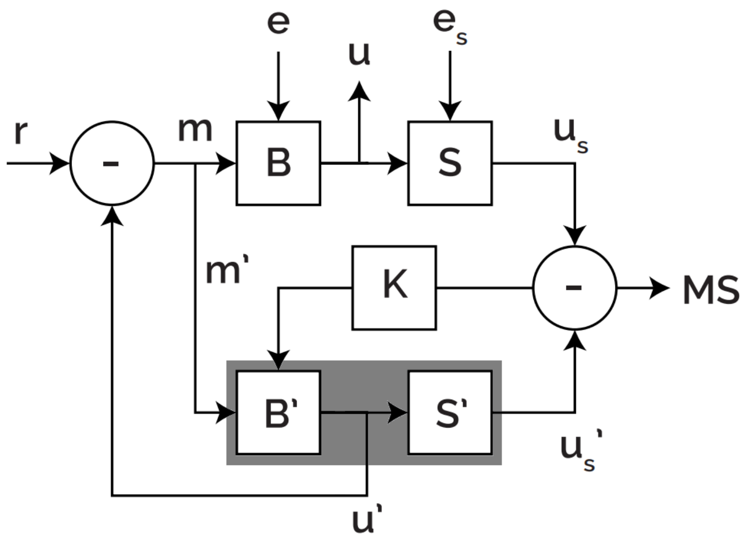

Figure 1.1 Simplified model of the Motion Sickness Theory (MST).

The model's inputs are the desired bodily state (**r**), based on which motor commands (**m**) are sent to the muscles in the body (B). Simultaneously, an "efference copy" (**m'**) is send to the internal neural representation of the body (B'). Thus, this part of the model predicts the effect of motor commands on the body and subsequently also the senses (S'). The combined internal representations of both the body and the senses are also referred to as an "internal model" or "neural store" (Oman, 1982). External physical perturbations, (**e**), such as a moving environment or push to the body, can also affect the actual bodily state (**u**). S represents the sensory processes –visual, vestibular and proprioceptive–, which is in part dependent on B, and in part on factors that can be unrelated to bodily state such as artificial visual motion and galvanic stimulation, ($\mathbf{e_s}$). In parallel, S' refers to the internal representation of the senses. While the senses lead to an estimation of the state of the body, ($\mathbf{u_s}$), the internal representation creates an *expected* sensed orientation ($\mathbf{u_s'}$). The difference or conflict between these two states is fed back to the internal model, possibly being modulated by a combination of factors as represented by K. If this conflict is sufficiently large for a prolonged period, motion sickness occurs, as hypothesised by Oman (1982) and Bles et al. (1998). The latter put an emphasis on body orientation as part of the overall state of the body in particular.

The actual bodily orientation (**u**) in the real world, is naturally only perceived indirectly through the confines of our senses. Finally, **u'** represents the eventual, functional, neural estimate of orientation. This model has been shown to predict a number of motion sickness characteristics fairly well, in particular for vertical cyclic motion (Bos & Bles, 1998). In addition, there are sound theoretical grounds to assume a neural mechanism resembling an efference copy exist. Namely, controlling a motor system using only directly sensory input (S) is suboptimal for two reasons. Firstly, it is too slow, as e.g. auditory and visual reaction times are generally found to be at least 200ms (Jain et al., 2015). Secondly, a feedback signal is required for motor control to perform optimally given imperfect sensors (see e.g. Kuo, 2002), and our senses are not perfect sensors. The MST model is of particular relevance with regards to the role of anticipation in motion sickness, as discussed in chapters 6 and 7, where it serves as an important theoretical basis for the research questions and interpretation of the findings.

1.3 Effects of physical and apparent motion

While generally motion sickness occurs during physical motion, not all motion is equal in its effect, and many factors influence what situations lead to motion sickness in which individuals. For instance, motion sickness is frequency dependent, as frequencies around 0.2 Hz are consistently found to be more nauseating compared to higher or lower frequencies (O'Hanlon & McCauley, 1974; Golding et al., 2001). This relation is mainly established for vertical motion, as historically and incited by WOII, motion sickness research initially focused on seasickness (Hemingway, 1942, Alexander et al., 1945), but appears to be similar for horizontal motion (Golding et al., 2001; Donohew & Griffin, 2004), and visual motion (Diels & Howarth, 2013). This implies that on board a ship, certain wave periods might be more detrimental than others, and that in a car some meandering roads might be more problematic than others.

The effect of provocative motion can be exacerbated or alleviated by non-vestibular sensory information, such as visual information. For instance, motion sickness is aggravated when reading a book in a moving car, or below deck at sea (Manning & Stewart, 1949, Bles et al., 1998). This is caused by the discrepancy between the visual information, i.e. the view on the car interior suggesting a stationary situation, and vestibular information, i.e. sensing the physical car motion. Conversely, congruent sensory information, e.g. looking at the earth-fixed horizon when on a moving ship, can alleviate motion sickness (Rolnick & Bles, 1989; Bos et al., 2008). The beneficial effect of an earth-fixed reference frame persists even when this is presented artificially (Feenstra et al., 2011; Tal et al., 2012).

Motion sickness can even occur even when physical motion is absent. Visual images that suggest motion can lead to 'vection', an illusory sense of self-motion (Fischer & Kornmüller, 1930; Dichgans & Brandt, 1973). Subsequently, the conflict between the sensation of motion resulting from the visual input and the vestibular information indicating the individual is in fact stationary, can lead to visually induced motion sickness (Keshavarz et al., 2015; Hettinger et al., 2014). Interestingly, those without functioning organs of balance also do not suffer from visually induced motion sickness, (Cheung et al. 1991; Johnson et al., 1999), while blind people can get motion sick from vestibular stimulation (Graybiel, 1970), underscoring that a vestibular component is fundamental in motion sickness.

1.4 How to measure motion sickness

Physiological markers correlating with motion sickness have been reported, such as galvanic skin response, temperature, heartrate, or blinking (Hemingway, 1945; Min et al., 2004; Dennison et al., 2016). However, comparison between individuals using such measures is extremely problematic due to highly divergent baseline scores. Within-subjects comparison is also problematic, as for instance temperature fluctuates within an individual even over the course of a single day. However, one well-defined and easily observable physiological reaction to motion sickness exists: vomiting. Simply referred to as the "motion sickness incidence” (MSI), the percentage of a population that has reached the limit of vomiting within a certain interval of time, is the basis for some principal research on motion sickness (e.g., O’Hanlon & McCauley, 1974; ISO 2631-1, 1997). However, the use of vomiting as a measure of sickness has several shortcomings. Firstly, extensive exposure is required to reach vomiting, while a wide range of discomfort exists before that – e.g. the majority of drives in which carsickness is reported do not culminate in vomiting (Turner & Griffin, 1999a), as will also be discussed in chapter 2. Secondly, provided that other informative measures exist, deliberately exposing participants to the point of emesis can be considered unethical (World Medical Association, 2013) if the same principal knowledge can be gained with less malaise.

As such, most studies on the topic of motion sickness use variations of subjective rating scales, scoring of symptoms, or a combination thereof. For example, the simulator sickness questionnaire (SSQ; Kennedy et al., 1993), scores 16 symptoms separately in a 4-point scale. Although specifically designed for simulators, the SSQ is also often used in real life conditions and lab experiments. However, because the SSQ is a multi-item questionnaire, collection requires a minute or two, and can therefore not easily be repeatedly applied during the exposure to a provocative stimulus. Subjective rating scales that are expressed with a single number, e.g. 0 to 10 defined as feeling fine to vomiting, have the advantage of being quick to be expressed and recorded. However, a drawback is that such scales might not be consistent across subjects, as some might judge a 5 as some discomfort, while others might consider it severe nausea. The misery scale (MISC; Bos et al., 2005) is an 11-point ordinal scale, rating the severity of initial non-nausea symptoms from 0-5, severity of nausea from 6-9, and vomiting as 10. This scale combines a numerical value with clearly demarked transitions associated with symptoms. When familiarised with it, subjects can easily report on their state within a second, allowing repeated application within experimental trials, even with eyes closed. The MISC is used in all experimental studies in this thesis, as these studies measure motion sickness during continuous exposure to provocative stimuli.

One complication that should be mentioned when investigating motion sickness is that individual susceptibility varies widely.

Fortunately, a validated questionnaire to assess a persons' motion sickness susceptibility exists, the motion sickness susceptibility questionnaire, MSSQ (Golding, 1998; MSSQ short: Golding, 2006). Nevertheless, this scale only gives an indication of susceptibility, and using a between-subjects design to study motion sickness comes with the risk that susceptibility to a (novel) motion stimulus varies widely. Therefore, in the experimental studies in this thesis, a within-subjects design is used. In addition to these inter-individual differences, susceptibility to motion sickness is affected by age and sex (Paillard et al., 2013). It is generally found that babies are immune, but young children become highly susceptible, while later in life, susceptibility again appears to decline with age (Bos at al., 2007). A genetic component to motion sickness susceptibility also has been reported (Bakwin, 1971; Sharma, 1980). A correlation of about .7 between the susceptibility to various motion environments has been suggested (Miller & Graybiel, 1972; Golding, 2006; Lackner, 2014). The wide variation in susceptibility is, again, the reason to refrain from between subject study designs, as these would require a multitude of participants as compared to within-subject studies (Faul et al., 2007).

A factor, possibly related to the above, which explains why individuals react differently to provocative motion is that of perceptual style. The manner by which visual information is weighted compared to vestibular information differs among individuals, as can be measured by the rod-and-frame test (Sigman et al., 1979). For instance, individuals that are more influenced by visual cues to orient themselves in space are found to be more susceptible to simulator sickness (Barrett & Thornton, 1968). This difference in visual style might also explain why some individuals are more susceptible to some forms more than others (e.g. Kennedy et al., 2010). Another possible explanation for the differences between individuals is that frequency dependency is not necessarily similar for all individuals: some might be more sensitive to either lower or higher frequencies of motion compared to the average peak sensitivity at about 0.2 Hz. There is also some evidence that for horizontal motion, frequency dependence is different than for vertical motion, (Golding & Markey, 1996; Griffin & Mills, 2002). Notably, even if also peaking at around 0.2 Hz, the function indicating horizontal motion susceptibility depending on frequency might be different (Golding at al., 2001). While the exact reasons are not fully known, it can be stated that individuals differ greatly in motion sickness susceptibility, and that this poses both a challenge when designing experimental studies, more so when it comes to predicting the effect a novel motion stimulus will have on participants.

Today, we do not only travel long distances by ship and become seasick, we move ourselves by means of a wide variety of motorised transport. Virtually all such forms can, occasionally, lead to motion sickness, and are subsequently called airsickness, train sickness, space sickness, or –the main focus of this thesis– carsickness.

1.5 Carsickness

Carsickness is a form of motion sickness that by definition occurs in cars or other road vehicles such as coaches. While it is not fundamentally different from motion sickness in other transport modes such as trains, planes and even ships, there are nevertheless several typical discernible aspects to carsickness that sets it apart. First, cars are occupied by drivers and passengers, two types of agents with widely different sensory and cognitive processes in their interaction with the internal car environment. Secondly, as a passenger, both what you do and where your look can have a considerable impact on carsickness. Thirdly, anticipation is known to play an important role in developing carsickness, and can be facilitated by what you see, or know, is coming in terms of car motion. Lastly, the type of road, driving style, and car suspension can also influence vehicle motion and thereby impact carsickness. Although important, the already well-documented impact of raw physical (vehicle) motions on motion sickness are not the focus of this thesis, which instead focuses on what factors from the individual's perspective influence carsickness, such as vision and anticipation.

Considering there are estimated to be over 1 billion cars in the world (Plunket, 2007), the amount of literature on carsickness is surprisingly limited, especially considering the majority of car passengers has experienced some carsickness in the last 10 years (Reason & Brand, 1975; chapter 2). However, most car users are drivers, and drivers rarely get carsick (Rolnick & Lubow, 1991). Generally, having control over a motion has been found to reduce motion sickness (Dong et al., 2011; Chen et al., 2012). This has been explained by the fact that a driver can anticipate upcoming motion, both immediate through control of the vehicle and in terms of upcoming traffic and road conditions, reducing the incongruence between anticipated and sensed motion that underlies motion sickness. Being a passenger is more problematic. Especially if vision outside is obstructed or limited, carsickness is considerably aggravated (Griffin & Newman, 2004; Perrin et al., 2013; Probst et al., 1982).

What is different in self-driving vehicles? In particular, in autonomous vehicles, occupants will shift from drivers to passengers, and thus it is expected that carsickness will become considerably more prevalent (Diels & Bos, 2016). Additionally, occupants will want to engage in non-driving activities (Zakharenko, 2016; Steck et al., 2018) and are thereby at an even more substantial risk of experiencing carsickness, due to a reduced view outside and inability to anticipate the motion of the vehicle (Diels et al., 2016; Kyriakidis et al., 2017, Le Vine et al., 2015; Wada, 2016). The increasing interest in automated vehicles might therefore also explain the increase of interest in carsickness the past several years (Wada et al., 2012; Diels, 2014; Perrin et al., 2013; Isu et al., 2014; Sivak & Schoettle, 2015; Diels & Bos, 2016; Wada, 2016; Wada & Yoshida, 2016; Lampinen, 2017; Sawabe et al., 2017; McGill et al., 2017; Karjanto et al., 2018; Dizio et al., 2018; Smyth et al., 2018). Self-driving cars, sometimes called *autonomous* cars or (highly) *automated* cars, are thought to become commonplace and subsequently even dominant as the main way of transport in the next several decades (Diels & Bos, 2016; SAE, 2014). Especially for shared mobility, carsickness might be an dampening influence on its acceptance (Diels et al., 2017). However, how much more and importantly precisely why carsickness will occur in autonomous vehicles is not fully known.

In addition to vision, seating orientation is known to impact carsickness. This might be interesting in the context of autonomous vehicles (Salter at al., 2019), especially the consequences if the occupant is free to recline to a laying position. A forward seating position in vehicles that allows for an increased view on the road ahead has been found to be beneficial in reducing carsickness (Turner & Griffin, 1999a, Turner & Griffin, 1999b; Mills & Griffin, 2000; chapter 3). Interestingly, laying supine is more beneficial in preventing motion sickness as compared to sitting upright (Golding et al., 1995; Vogel et al., 1982; Manning & Stewart, 1949). This might be the result of a reduced importance of the human body to maintain posture when laying down, and thus less importance of sensory rearrangement as described above. An active suspension system has also been found to potentially lower motion sickness (Dizio et al., 2018; Golding et al., 2003). Nevertheless, in studies where vision is also an independent variable (i.e. is manipulated), it is often found to be the primary dominant factor affecting motion sickness (e.g. Bijveld et al., 2008; Wada & Yoshida, 2016).

Autonomous vehicles can lead to safer roads, reduce fuel consumption, and increase productivity during transit (Greenblatt & Shaheen, 2015). However, if carsickness proves to be highly problematic for a large portion of potential users of self-driving cars, the acceptance of autonomous vehicles by the general public is at risk. Therefore, gaining knowledge on the mechanisms of carsickness and potential insight into mitigating it are of importance to the scientific community, the automotive industry, and by extension to the general population. Hopefully, the studies covered in this thesis will contribute in part to a future of comfortable and safe autonomous vehicles.

1.6 Aim and outline of thesis

In **this chapter**, I outlined the theoretical background and motivation for the research in this thesis. In **chapter 2**, we examined the current state of carsickness by means of an extensive survey done in five different countries across various continents. As the most recent survey data prior to this study stem from the 1970s (Reason & Brand, 1975), this chapter both provides a valuable insight in the present scope of the problem of carsickness today, and also lays the foundation to examine the possible impact of autonomous vehicles.

One of the primary factors exacerbating carsickness is limited vision, e.g. when reading or working on a laptop. In autonomous vehicles the occupant will be more inclined to use such devices, as he or she is now a passenger with no driving task (Steck et al., 2018). Therefore, in **chapter 3**, we explore the effect of display positioning and associated availability of peripheral vision on carsickness. In a car performing a slalom on a test track, we compared two conditions of identical slalom driving, in which participants performed a task on a display placed either at eye-height or at the height of the glove compartment. This chapter thus primarily explores the link between the magnitude of a visual-vestibular conflict and subsequent motion sickness in an on-road setting.

Assuming an occupant is engaged with a display, peripheral vision can still offer vision out-the-window and thus a beneficial earth-fixed reference frame (as discussed in chapter 3). However, an electronic display could also concurrently be used to present additional information, such as an artificial earth-fixed frame. There is evidence that adding artificial images, such as an artificial horizon in a ship simulator, can reduce motion sickness (Tal et al., 2012; Bos et al., 2012). This might also be a promising approach in cars by means of a 'see-through' display (Miksch et al., 2016). However, artificial visuals are known to be able to cause vection, a sense of self motion, but do not do so consistently and can lead to visually induced motion sickness (Keshavarz et al., 2015). Such artificial visuals employed as countermeasures might thus cause more motion sickness then they prevent, as visual motion can even be more provocative than the motion it suggests (Eyeson et al., 1996). Therefore, in **chapter 4** we explored what a constant optic flow does in such a situation, i.e. how vection as a result of constant optic flow relates to motion sickness.

Simulators offer a safe research environment and have methodological advantages in their degree of replicability of motion and visual cues compared to on-road studies. However, most moving base simulators are highly limited in their motion envelope, and artificial visuals of simulators can potentially cause simulator sickness. In **chapter** 5 we explored the possibility to use simulators to investigate carsickness. In automated driving, the moment of transfer of control back to the passenger when entering an area where automated driving is not supported (SAE, 2014) could pose an increased safety risk due to a combination of reduced situational awareness and impeded driving abilities as a result of motion sickness (Rolnick & Bles, 1989; Bos, 2004). Exactly such scenarios could be safely studied in a driving simulator, if it can incite motion sickness levels similar to carsickness.

While vision on the road ahead is important in reducing carsickness, as it is often reported (Griffin & Newman, 2004; Salter et al., 2019), this is mainly explained as resulting from a reduced visual-vestibular conflict. However, vision on the road and traffic ahead in a vehicle also helps the occupant to anticipate upcoming vehicle motion, e.g. due to braking or cornering. Yet, relatively little is known about the effect of being able to anticipate provocative motion, and subsequent motion sickness. Therefore, in **chapter 6** we examined specifically the role of anticipation on motion sickness. By means of three conditions of varying motion we attempted to answer the question to what extent the unpredictability in timing or direction makes a motion more nauseating, compared to similar but predictable motion. Given our findings, there might be a reason to assume that the role of anticipation is more important in carsickness as compared to visual-vestibular interactions than previously thought.

In **chapter 7** we further explored the effect of anticipation on motion sickness. This time, we sought to investigate whether anticipation to upcoming motion can be aided by external means. We theorized that motion sickness could potentially be reduced when information on upcoming motion is presented auditorily, as this reduced the discrepancy between sensed and expected motion. The same experimental set-up was used as in chapter 6, with similar motion that was now unpredictable in both timing and direction. In one condition participants received informative auditory cues offering knowledge on the timing and direction of the upcoming erratic motion. In the other condition, similar auditory cues were presented at non-informative times, with random directionality. While it is known that anticipation can reduce motion sickness, it has never been established that this can be facilitated by means of auditory, or other novel channels of, information. The findings in this chapter could potentially be readily translated to more practical research into countermeasures again motion sickness. For instance, these could be implemented especially in self-driving vehicles, since upcoming vehicle motions are generally planned in advance by the vehicle computer, in a similar timeframe as the cues we utilized.

In Table 1.1 an overview is shown of the research questions addressed in chapters 2 to 7, in addition to their relevance to this thesis. Finally, in **chapter 8,** I integrate and extensively discuss the findings of the previous chapters and reflect on both their theoretical implications and examine their relevance in future research and possible real world applications.

Table 1.1. Overview of the research questions addressed in the following chapters.

Chapter	Main research question	Relevance to thesis
2	What is the current incidence and severity of carsickness?	Survey study which gives insight in the scope of the current problem of carsickness, and its potential risk factors in self-driving cars
3	Does increased peripheral vision reduce carsickness during display use?	Assuming occupants will use a display in a self-driving car, display placement could be optimized to reduce carsickness
4	Does vection or do alterations in vection cause visually induced motion sickness?	Explores whether a visual countermeasure (i.e. a 'see-through' display') against carsickness is feasible or if it will give problems with vection and visually induced motion sickness
5	Can moving base driving simulators be used to study carsickness?	Using simulators would be particularly well suited for automated driving studies
6	Is unpredictable motion more sickening than predictable motion?	The importance of anticipation in carsickness is not fully known, especially the potential magnitude of the effect
7	Can unpredictable motion be made less provocative with auditory cues?	In self-driving vehicles, vehicle motion of the next several seconds is generally known. If this information can be used to reduce carsickness, this would be highly informative

Chapter 2

An international survey on incidence and modulating factors of carsickness

Schmidt, E.A., Kuiper, O.X., Wolter, S., Diels, C., Bos J.E. (Under Revision) An international survey on incidence and modulating factors of carsickness.

Abstract

Objective: Given a global increase of interest in carsickness driven by the development of automated vehicles, this survey intended to assess a status quo of carsickness across different nationalities. It has been reported that about two in three people experience carsickness at some point in their life (Reason and Brand, 1975). However, little is known about current numbers of sufferers, about cultural differences, nor which modulating factors are being perceived as most relevant.

Methods: We conducted an online survey on the occurrence of carsickness, and associated factors, with 4,479 participants in Brazil, China, Germany, UK and USA.

Results: 46% of participants indicated to have experienced some degree of carsickness in the past five years as passenger in a car. When including childhood experiences, this rate increases to 59%, which comes close to the 1975 findings of Reason and Brand. The highest incidence was reported in China, the lowest in Germany. In all countries, men and older participants reported a lower incidence of carsickness as compared to females and younger participants. The main modulating factors were found to be driving dynamics, visual activities, and low air quality. Visual activities and low air quality were reported to have the shortest latencies until symptom onset.

Conclusion: We found carsickness to be a problem still affecting the majority of passengers presently, and discuss how its occurrence relates to in-transit activities (e.g. reading or using a display), and other modes of transport. The study provides a sound basis to further study what factors underlie carsickness and to investigate countermeasures can potentially reduce carsickness.

2.1. Introduction

2.1.1 Motion Sickness

Exposure to motion can lead to motion sickness, for instance in a car on windy roads. This state of discomfort is theorized to result from the discrepancy between anticipated and sensed motion (Reason and Brand, 1975; Oman, 1990; Bles et al., 1998), and occurs predominantly with low-frequency motion (O'Hanlon & McCauley, 1974). Although large inter-individual differences in terms of susceptibility are observed (Reason & Brand, 1975; Bos et al., 2005), once it occurs, motion sickness initially manifests itself as a subset of symptoms such as (cold) sweating, dizziness, pallor, salivation, and apathy (Money, 1970). If the exposure to motion continues, these symptoms may be followed by nausea, culminating in retching and finally vomiting.

2.1.2 Carsickness

Carsickness is a form of motion sickness that occurs in road vehicles. It is principally caused by the vehicle's motion with more dynamic driving styles, i.e. higher accelerations, leading to elevated sickness levels (Turner & Griffin, 1999a). In addition, there are several other factors affecting the occurrence of carsickness. The most important one concerns the observation that drivers suffer considerably less from carsickness than passengers do, irrespective of being exposed to the same motion (Rolnick & Lubow, 1991). This can largely be explained by the fact that drivers can better anticipate the motion of the vehicle as compared to passengers, reducing discrepancies between expected and sensed motion.

Another important factor in understanding carsickness is vision. Visual-vestibular discrepancies, such as when reading a book or watching a computer screen in a moving vehicle, can exacerbate motion sickness considerably (Bles et al., 1998; Bos et al., 2008; Kuiper et al., 2018; Diels et al., 2016). Conversely, ample out-the-window vision can reduce carsickness, especially when looking at the road ahead. This beneficial effect likely involves the possibility to anticipate upcoming motion (Probst et al., 1982; Griffin & Newman, 2004; Turner and Griffin, 1999b; Perrin et al., 2013). The possibility to anticipate is also reduced by a backward seated orientation, which is found to increase sickness (Turner & Griffin, 1999b; Griffin and Newman, 2004; Salter et al., 2019). Being exposed to critical motion with eyes closed is found to be less provocative, possibly on par with out-the-window vision (Griffin & Newman, 2004; Bos et al., 2005).

Women are found to be considerably more susceptible to motion sickness compared to men (see e.g. Klosterhalfen et al., 2005; Bos et al., 2007; Paillard et al, 2013). This, however, is typically observed when using self-ratings, and can be assumed to be a gender (i.e., cultural), rather than a sexual (i.e., physiological) difference. When focusing on vomiting, for example, the difference is generally not observed (Cheung & Hofer, 2002). Susceptibility to motion sickness has been found to increase with age peaking in youth, and to decrease thereafter (Bos et al., 2007). Susceptibility to motion sickness in general is found to also have a genetic component (Hromatka et al., 2015; Bakwin, 1971). This is reflected in the findings that Asian individuals are more susceptible to motion sickness compared to Caucasians (Stern et al., 1996; Klosterhalfen et al., 2005). To our knowledge, the vast majority of literature on carsickness does not take ethnicity into account. This might lead to an underestimation of the occurrence of carsickness when translating general observations to Asian populations in particular or an overestimation vice versa.

Lastly, there are several other factors affecting motion sickness, which we will only mention briefly here. Lying on one's back, for example, reduces sickness (Vogel et al., 1982; Golding et al., 1995). The effect of odours is still somewhat controversial, yet speaking in favour of unpleasant odours having a negative effect, in particular when associated with the vehicle at issue (Paillard et al., 2010; Perrin et al., 2013 versus Paillard et al., 2014). Airflow on the other hand has been shown to significantly reduce motion sickness (D'Amour et al., 2017). Mental expectation of becoming sick might increase its occurrence as a self-fulfilling prophecy (Eden & Zuk, 1995), while mental distraction has been shown to decrease sickness severity (Bos, 2015). The latter may also explain the beneficial effects of pleasant music (Keshavarz & Hecht, 2014).

According to Reason and Brand (1975), in cars about two thirds of all passengers have suffered from sickness at some moment throughout their lifetime, with about half of them also reaching the limit of vomiting. A field survey of coach passengers by Turner & Griffin (1999b) indicated that 37% of these had been motion sick in cars before, which was 23% in coaches. The reason for the lower incidence rate in this study compared to that of Reason and Brand is difficult to determine, but may be based on effects of habituation, i.e., a reduction of sickness by repeated exposure due to many respondents in Turner and Griffin's study travelling by bus on a regular basis. Obviously, the inconsistency between these data sets justifies an update based on comparable criteria for different transport modes. Further, the age of the data sets, the limitation to one specific part of the world, as well as the lack of comparability across transport modes defined the need for this study.

2.1.3 Aim of Study

Given the dated literature on the incidence of carsickness, coupled with the observation that globally cars increasingly account for the vast majority of passenger kilometres (see e.g., Eurostat, 2018), an update of the incidence of carsickness would be valuable. In addition, no data exists on the effect of ethnicity on carsickness. Another development that makes survey data on carsickness more relevant, is the expected introduction of automated vehicles over the coming decades (Litman, 2014), as this will increase the kilometres travelled by car passengers, especially engaged in non-driving related tasks. Automated driving can hence be expected to increase the occurrence of carsickness (Diels & Bos, 2016). Therefore, the aim of this study is to conduct a large scale survey to assess the incidence of carsickness across several countries, including modulating factors of carsickness and how it relates to other modes of transport.

2.2. Method

We aimed at collecting data in several countries with an extensive use of cars and public transportation. To collect data from a large number of respondents across these countries in a consistent way, we elected to utilize an online survey. We only included participants that regularly used public transport and/or privately owned cars, since these are the populations potentially at risk of carsickness. Based on these conditions, as well as the goal to include countries from different continents, we selected Brazil, the People's Republic of China, Germany, the United Kingdom, and the United States of America for our survey.

2.2.1 Questionnaire

A questionnaire was developed in the English language, programmed, tested and optimized for usability and language with a sample of experts, among whom native English speakers. Afterwards professional translators translated the questionnaire into Mandarin Chinese, German and Portuguese. Bilinguals finally checked these versions for consistency with the original English draft.

In accordance with the basic items discussed in the introduction, the survey consisted of the following sections: 1) Welcome and assurance of anonymity. 2) Demographics including gender, age, and vehicle ownership. 3) Seating choices in a hypothetical transportation situation. 4) Transportation behaviour, frequency of motion sickness in different transport modes, and 5) Modulating factors and countermeasures. The wording of each item of relevance for this study part will be reported in the results section.

2.2.2 Participants, Sampling Procedure and Data Collection

A market research agency recruited the participants, using online panels in which specific demographics could be selected. We aimed at about a thousand completed surveys per country. Respondents were selected only to ensure the sample 1) consisted of those over 18 years of age, 2) was representative of the gender and age distribution of car owners in that country, and 3) consisted of 50% for whom a car was the primary mode of transport and 50% for whom this was public transportation.

Based on these criteria, a total of 16,315 individuals were invited to participate. After survey completion, participants received credits that could be collected and exchanged for vouchers of commercial online platforms.

Data collection took place from June 31st to August 18th 2017. 45.5% of the invitees started the survey, of whom 73% also completed it. Median duration to complete the total survey was 13 minutes. The market research agency delivered 4,500 quality-screened cases, of which 21 had to be excluded by the researchers due to some obvious inconsistencies, resulting in a total sample of N = 4,479 cases.

2.2.3 Basic Sample Properties: Demographics and Transportation Behaviour

Figure 2.1 shows the gender and age distribution for each of the countries assessed. Because the sample was primarily recruited to resemble the car owner population of each country, there are clear differences between countries with regards to the age distributions. In the presented data on general motion sickness likelihood by gender, age and country, these differences will be attributed for by reporting data for each subgroup and employing a binary logistic regression model.

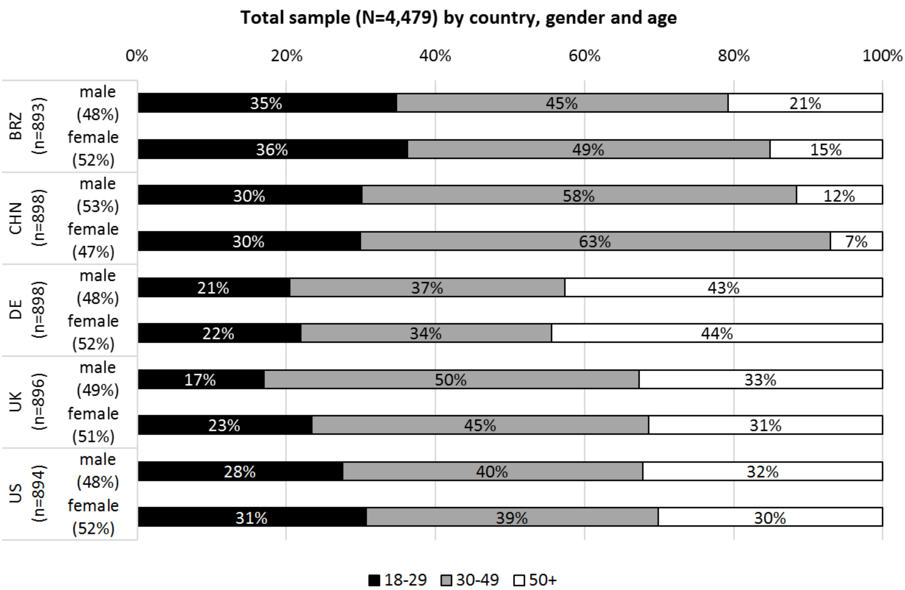

Figure 2.1. Final sample composition (N = 4,479) by country, gender and age.

Overall, there was sufficient general mobility experience in the sample, as 92.6% used any form of mobility "a few times a week or more", 98.9% "a few times a month or more" and 99.8% "a few times a year or more". Figure 2.2 displays the frequency of use for the different transport modes assessed. It can be seen that the predominant use of either public transport or of a car/truck/van as a recruitment criterion was successful in enabling a sufficient variance in use of different transport modes. All three vehicle types were named in the English surveys, since especially in the United States trucks and vans are seen as separate vehicle types than cars. For ease of reading, in the following we will only refer to "cars".

To ensure a sufficient level of exposure, for all incidence data presented in the results section, the sample was reduced to those that actually use the respective transport mode at least "a few times a year" resulting in N = 4,268 cases.

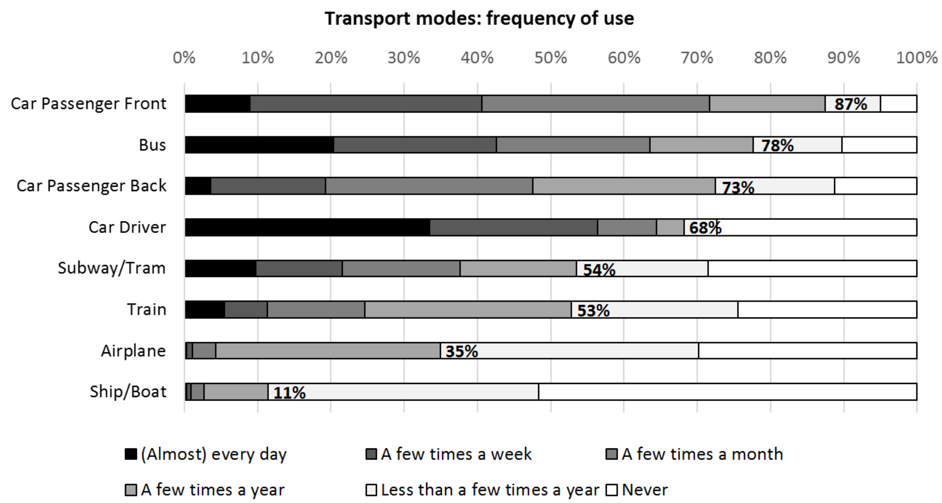

Figure 2.2. Frequency of use for each transport mode. The numbers added to the graph indicate the percentage of participants that use a certain mode of transport at least "a few times a year". This fraction created the basis for all incidence estimates reported in the results section. Item wording: *"Below is a list of modes of transportation. During the past five years, how often have you used each of the following?"*

2.2.5 Definition and Incidence of Motion Sickness

In order to ensure the same understanding of motion sickness in each country, a definition was provided at the start of the respective section of the survey: *"Motion sickness is a condition of feeling unwell which can occur when traveling in anything from ships (seasickness), cars (carsickness), to rollercoasters. Symptoms differ between people but often include fatigue, dizziness, sweating, nausea and eventually vomiting*."

All motion sickness incidence rates were then based on the item *"At any moment in the last five years, have you experienced any symptoms of motion sickness while…"*. A person having experienced motion sickness was then defined as anyone who did not answer *"No, never"* but "*Yes, "* plus any of the options indicating the actual frequency (*"…rarely"*; *"…sometimes"*; *"…often"*; *"…(almost) always"*).

2.2.6 Statistical Analysis

Wherever applicable, in order to be able to estimate proportions for the population, 95% confidence intervals will be displayed. Effects of gender, age, and country will be reported by means of a binary logistic regression, testing the association between those three factors and the likelihood of reporting carsickness. The effect of different modulating factors on the onset time of carsickness, will be tested by means of a one-way between-subjects ANOVA supplemented by a post-hoc Dunnet multiple comparisons test with *driving dynamics* being the control level. For all statistical tests, the alpha levels are set to .05. Given the comparably large sample size, the statistical tests can be expected to be able to detect effect sizes even of small magnitude.

2.3. Results

2.3.1 Incidence, Frequency and Severity of Motion Sickness

In total, of all participants that had travelled in a car at least a few times a year (N = 4,268), 45.6% (95%-*CI*: 44.1% - 47.1%) reported to have experienced carsickness at some point in the past five years. If this analysis is only limited to those who had travelled as a *passenger* in a car at least a few times a year (N = 4,084), this rate increases to 46.3% (95%-CI: 44.8% - 47.9%). The higher rate for the latter can be explained by the fact that car occupants that only travel in a car as a driver, which are excluded in that analysis, typically report less motion sickness.

Figure 2.3 indicates that for car passengers, the position on the back seat results in the highest incidence (46.4%; *CI*: 44.7% - 48.1%), which is significantly different from the incidence on the front seat position (36.7%; *CI*: 34.2% - 37.2%) as well as in the car driver position (17.2%; *CI*: 15.9% - 18.6%). Of all transport modes, motion sickness incidence was highest in Boat/Ship travel (62.1%; *CI*: 58.0% - 66.4%) and significantly different from all other modes of transport.

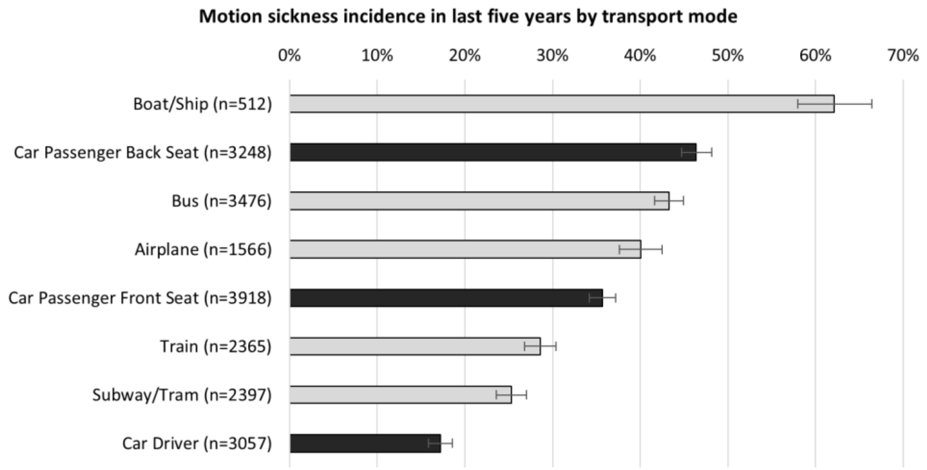

Figure 2.3. Motion sickness incidence in the last five years by mode of transport sorted by incidence. Only participants are included that have been travelling in the respective transport mode at least "a few times a year". The dark grey bars indicate the three different roles while travelling in a car. Error bars indicate the 95%-confidence interval for proportions. Item wording: *"At any moment in the last five years, have you experienced any symptoms of motion sickness while…"*

Figure 2.4. shows the frequency of carsickness broken down by answer categories. While the proportions in all other categories are well proportional to the overall incidence rate at each position in the vehicle, it seems worth noticing that an over proportionally high percentage of car drivers indicate to experience carsickness "*(almost) always*" (3.9%).

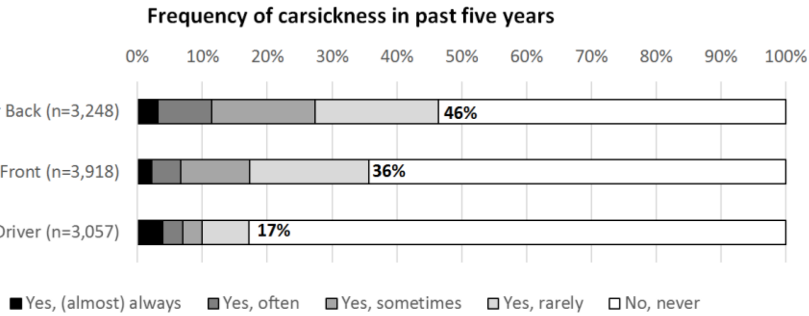

Figure 2.4. Frequency of carsickness in past five years. Only participants were included that have been travelling in a car at least "a few times a year". The numbers added to the graph indicate the percentage of participants that indicated to have experienced motion sickness in the respective position at any frequency. Item wording: *"At any moment in the last five years, have you experienced any symptoms of motion sickness while…"*

All car passengers that had reported carsickness (*n*=1,892) in the previous five years were given the choice between the statements "*I only experience motion sickness when I don't look outside the front window for some time and engage in other activities."* and *"Even if I look outside the entire time, it may happen that I become motion sick."*". 45.5% (CI: 43.2% - 47.7%) indicated that not looking outside is a necessary precursor for motion sickness to occur. 54.5% (CI: 52.3% - 56.8%) indicated that motion sickness may also occur when looking outside the moving vehicle. Figure 2.5 shows the severity of the worst incidence of carsickness in the past five years. A chi-square test revealed higher severity levels in the group that experiences motion sickness even when looking outside (χ^2 (4) = 71.43; p < .001).

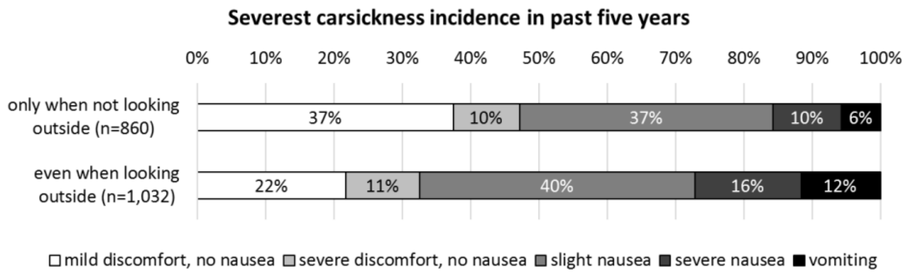

Figure 2.5. Severest carsickness incidence in past five years by carsickness type. Only participants included that have been travelling in a car at least "*a few times a year*". Item wording: *"Now please think about the worst incidence of motion sickness that you experienced over the past five years when riding in a car/truck/van. On a scale from 1 (mild discomfort) to 5 (vomiting), how severe were the symptoms you experienced?"*

In order to also consider carsickness along the entire lifespan, those participants that reported no carsickness in the previous five years were asked "*Did you experience any symptoms of motion sickness in a car at any other moment in your lifetime - including your childhood*?". Based on the overall sample of frequent car users, an additional 13.1% (CI: 10.3% - 16.0%; BRZ: 17.4%, CHN: 7.8%, DE: 13.0%, UK: 16.1%, US: 11.0%) indicated that this was the case resulting in an overall lifespan incidence of 59.4% (CI: 57.5% - 61.4%; BRZ: 62.3%, CHN: 70.4%, DE: 48.5%, UK: 59.5%, US: 55.6%).

2.3.2 Influence of Gender and Age

Figure 2.6 shows carsickness incidence in the past five years by country, gender and age. It is noticeable that there are very large differences between the individual cells reported. For instance, 81.7% of the Chinese females below the age of 30 reported carsickness, while only 11.5% of the Brazilian males 50 years and older did so. Yet, age and gender also seem to be present very consistently across countries. Looking at the proportions of reported carsickness within each country, China with 61.7% clearly had the highest proportion, while Brazil

(44.5%), US (44.2%), UK (42.8%) were in roughly the same range, and Germany showing the lowest proportion with 34.3%.

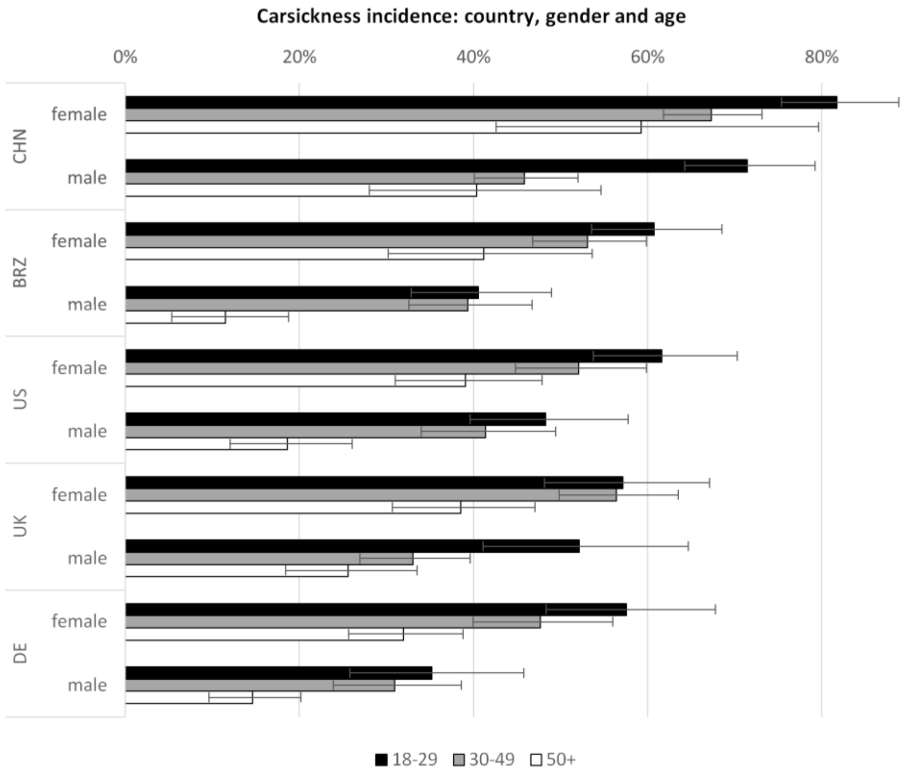

Figure 2.6. Carsickness incidence over the past five years by country, gender, and age. Only participants included that have been travelling in a car at least “a few times a year”. Error bars indicate the 95%-confidence intervals. Item wording: “*At any moment in the last five years, have you experienced any symptoms of motion sickness while…*”

Since the data showed no evidence for interactions of considerable size for the factors country, gender, or age group, only main effects were modelled in the binary logistic regression. Results indicated that there was a collective significant association between age, gender, country, and the likelihood of participants reporting carsickness ($\chi^2(7) = 427.62$, $p < .001$). The individual predictors were examined further and indicated that country ($\chi^2(7) = 97.74$, $p < .001$), gender ($\chi^2(7) = 135.46$, $p < .001$) and age group ($\chi^2(7) = 149.40$, $p < .001$)

were all significant predictors in the model. The total adjusted R^2 of the model was 7.15%.

Table 2.1 summarizes the odds ratios for the levels of each predictor – showing for instance that individuals belonging to the age group 18-29 have a more than three times higher chance of experiencing motion sickness than those individuals that belong to the age group 50 and older.

Table 2.1. Odds ratios. For each predictor the group with the lowest likelihood was chosen as the reference. Given all lower 95% CIs >1.00, all predictor levels differ significantly from the reference level.

Predictor	Level	Odds Ratio	Lower 95% CI	Upper 95% CI
Country	*Germany (Ref)*	*1.00*	-	-
	Brazil	1.25	1.02	1.53
	UK	1.37	1.12	1.68
	US	1.37	1.12	1.69
	China	2.62	2.13	3.23
Gender	*Male (Ref)*	*1.00*	-	-
	Female	2.12	1.86	2.41
Age Group	*50+ (Ref)*	*1.00*	-	-
	30-49	1.95	1.65	2.30
	18-29	3.02	2.53	3.63

3.3 Subjectively reported modulating factors

For this analysis N = 1,892 participants that had indicated to have been a passenger in a car at least a few times a year and to have experienced carsickness in the past five years were included. Participants indicated for several conditions, which were based on the existing literature as well as a pilot questionnaire, how likely they would experience carsickness under these conditions.

Figure 2.7 shows the percentage of participants that indicated to *likely* or *very likely* experience motion sickness under each of the indicated conditions (*N* = 1,892). For nine potential modulating factors significantly more than half of the participants indicated that they would at least *likely* experience carsickness under these conditions.

The factors that were reported to lead to most carsickness were those that can cause repeated lateral and longitudinal accelerations at considerable magnitude (many turns [71.8%], curvy roads [70.5%], stop-and-go traffic [56.9%]), aspects that influence subjective air quality (cigarette or exhaust smell) [71.2%], warm air [57.9%]) and different visual activities (reading [67.1%], writing [59.4%], using a device [61.7%], watching video [58.0%]).

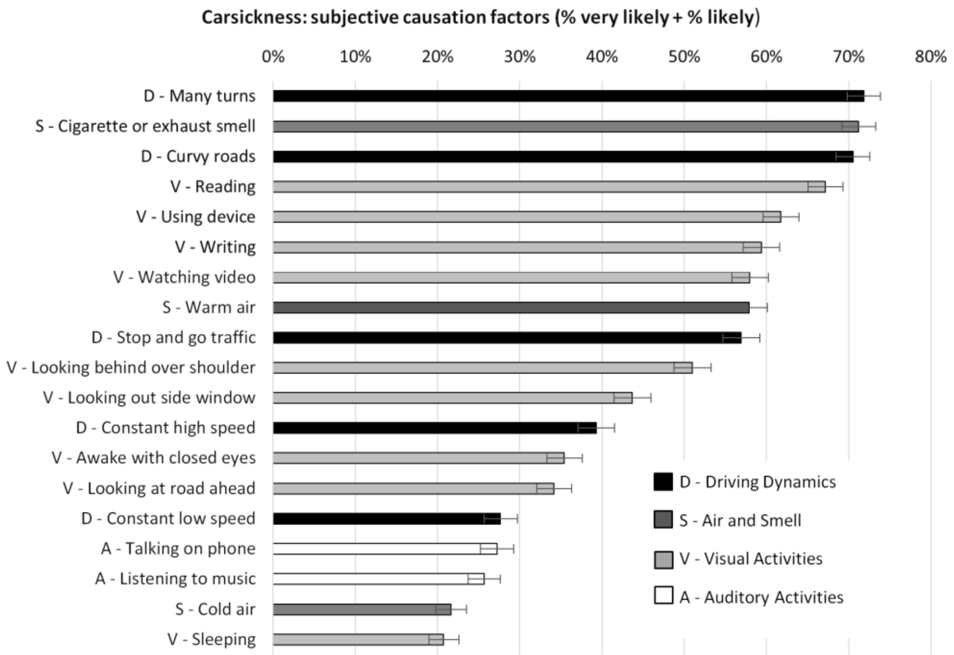

Figure 2.7. Percentage of participants indicating that they are *likely* or *very likely* to experience motion sickness under each of the indicated conditions. Differences in bar colours indicate the four different modalities. Error bars indicate 95% confidence intervals for proportions. Item wording: "*While a passenger in a car, how likely are you to experience motion sickness in the following situations?*"

2.3.4 Duration of modulating factors until start of symptoms

Participants were asked to estimate the duration until first symptoms appear for one (randomly chosen) modulating factor they rated highest in the previous assessment. To ensure a sufficient sample size per factor, it was decided to pool the data into three modalities based on the three highest rated modulating factors for each category. This resulted in pooling the data into *visual activities* (reading [*n* = 148], writing [*n* = 123], using a device [*n* = 96]), *driving dynamics* (many turns [*n* = 122], curvy roads [*n* = 105], stop and go traffic [*n* = 86]) and *air and smell* (cigarette or exhaust smell [*n* = 181], warm air [*n* = 63]). One extreme outlier that reported 10 hours of exposure until symptoms appeared was excluded.

The empirical cumulative distribution functions in Figure 2.8 illustrate the range of symptom onset times that were reported by the participants. Table 2.2 depicts the mean and median values.

Table 2.2. Descriptive statistics and confidence intervals for motion sickness onset time in minutes for each modulating factor cluster

Factor	n	Median	Mean	Lower 95% CI	Upper 95% CI
Air and Smell	245	10	13.84	11.59	16.09
Visual Activities	368	10	15.06	13.23	16.90
Driving Dynamics	315	15	18.90	16.92	20.89

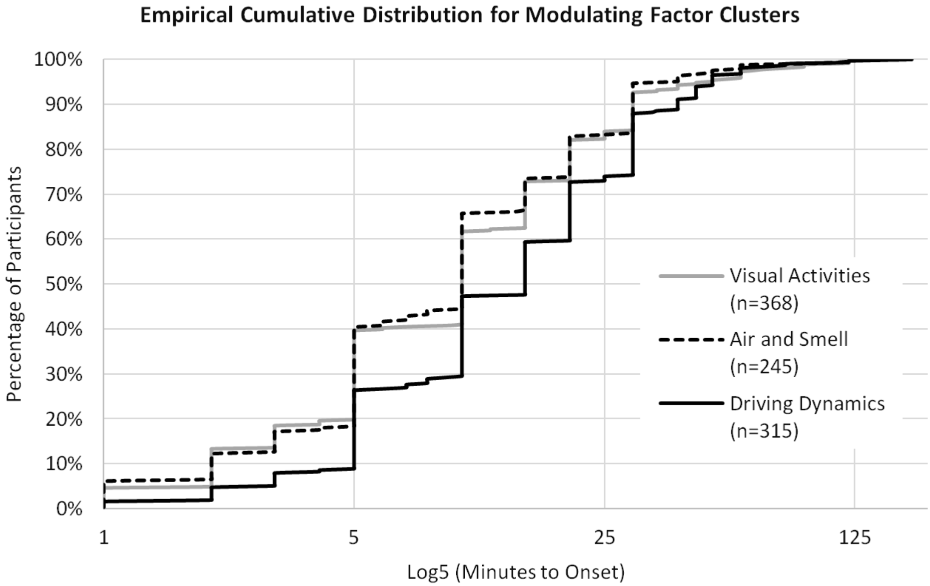

Figure 2.8. Empirical cumulative distribution for modulating factor clusters visual activities (reading writing; using a device), air and smell (cigarette or exhaust smell; warm air) and driving dynamics (many turns; curvy roads; stop and go traffic). Item wording: "*When being exposed to a situation (e.g. [Reading]) where you may end up become motion sick as a passenger in a car, how many minutes before you feel the first symptoms of motion sickness? Please make your best guess:*"

An one-way ANOVA revealed a significant effect of the three level factor *type of modulating factor* ($F(2, 925) = 6.39$; $p = .002$) indicating the presence of a difference between the three factor levels. A post-hoc Dunnet multiple comparison to test for differences in mean symptom onset times between the individual factor levels revealed that in comparison to *driving dynamics* both *visual activities* ($T(656) = -2.79$; $p = .010$) as well as *air and smell* ($T(554) = -3.31$; $p = .002$) showed significantly lower onset times.

2.4. Discussion

2.4.1 Carsickness Incidence

We found carsickness was experienced by 46% of car occupants in the last five years, or 59% when including their entire lifespan. These findings are close to those reported by Reason and Brand (1975), who found two-thirds of participants reporting some illness at any point in their lives. The (small) difference existent yet, may be explained by regional differences, which information is not clear from Reason and Brand. Carsickness therefore remains an issue affecting a similar proportion of car users as it did more than 40 years ago.

The present data are the first to explicitly compare carsickness incidence in different modes of transport. In comparison to Turner & Griffins (1999b) it is interesting that the incidence of travel sickness on the backseat of a car and in a bus seem be fairly comparable (48% vs. 45%) in our study, while Turner and Griffin found a considerable difference of 37% vs. 23%. Since the latter was assessed after an actual coach ride, their finding might be skewed by a selection bias, as individuals traveling by coaches might be less prone to experience sickness compared to the general population. The effects on reported sickness related to seating position and activity are in line with the hypothesis that the availability of out-the-window visual information as well being in control of the vehicle (as a driver) reduce the likelihood of carsickness. Last, it is worth mentioning that both rail-bound modes of transport (train and tram) seem to cause significantly less motion sickness as compared to the other modes of transport considered. A likely explanation is a lower magnitude of lateral, longitudinal as well as vertical accelerations (Förstberg, 2000; Perrson, 2008).

We found motion sickness to decrease monotonic with increasing age which is in line with other studies (Bos et al., 2007; Paillard et al., 2013). Also in line with literature (e.g. Klosterhalfen et al., 2005; Bos et al., 2007; Paillard et al, 2013), we found an effect of gender, with women reporting higher incidences of motion sickness by a factor of 2.12 as compared to males. Given the unclear evidence whether this is a physiological effect or a cultural effect resulting from self-reporting, we can only conclude that subjectively carsickness seems to be more of an issue in the female population. This might also make females more susceptible to benefit from countermeasures.

Respondents from China reported the highest levels of carsickness, while respondents from Germany reported the least (e.g. 58% vs. 40% in age group 30 to 49). Although nationality was determined by residence, rather than by ethnicity, especially China has a very low number of immigrants (Heberer, 2017). Therefore the relatively high susceptibility to motion sickness of found in China might very likely be attributed to genetics (Klosterhalfen et al., 2005). It remains unknown, however, whether factors like road design, traffic-density and frequency and type of non-driving activities are different between nationalities, and may be explanatory as well.

Interestingly, 3.9% of car drivers indicated to “almost always” experience motion sickness. A check of the data did not suggest this was the result of bad data (i.e. inconsistent respondents), rather, a small portion of drivers might consistently experience mild motion sickness. However, also since this is such a small subset, it is hard to draw any concrete conclusions based on this finding.

2.4.2 Modulating Factors

The overall picture of modulating factors is very well in line with the literature. Namely, brisk and high- intensity de-/accelerations, visual activities, and unpleasant odours are reported to increase motion sickness, while low-intensity dynamics, non-visual activities, looking outside, and sleeping are associated with reduced motion sickness. Apart from validating often heard anecdotal reports on these issues, these findings also validate the survey approach used here, and indicates that people have considerable awareness of relevant modulating factors.

One finding of particular interest is that looking at moving images (video) is rated as significantly less provoking than looking at stationary content (reading). This is in line with some recent studies (Isu et al., 2014; Schoettle & Sivak, 2009), but not with the assumption that adding potentially conflicting motion could lead to even more (visually induced) sickness (Keshavarz et al., 2015). A possible explanation might be the ability to sample the environment and still follow content which is possible with video but not with reading. In addition, a higher level of distraction from the video could be a beneficial factor (Bos, 2015). Furthermore, today passengers are most likely only interacting with rather small displays (e.g. smartphones) and the overall duration of engagement with video images might be rather low.

Concerning the reported exposure times until onset of first symptoms, the mean durations reported here (14 to 19 minutes depending on modality) are in line with other research that has shown significant levels of carsickness after ten minutes of exposure to potentially critical conditions (Griffin & Newman, 2004; Kuiper et al., 2018). Unsurprisingly for a survey study, participants report a very large range of durations. Additional modulating factors (visual activities, air and smell) were reported to cause motion sickness more quickly than provocative vehicle motion itself. This might be explained by the fact the potential detrimental visual factors might in fact often be accompanied by provocative vehicle dynamics, and thus trigger motions sickness more quickly than only provocative vehicle dynamics.

2.4.3 Methodological Limitations

Although the use of online panels has advantages and disadvantages (Evans & Mathur, 2005), one advantage is that they can have a higher attentional involvement than college student populations (Hauser & Schwarz, 2016). In general, online surveys may have the risk of leading to a biased sample due to not reaching individuals without internet access. However, in recent years, access to internet is widespread in the countries we selected and online surveys can be of equal quality to conventional studies (Hauser & Schwarz, 2016). Traditional pen-and-paper surveys have their own selection biases, e.g. even being limited to recruiting near the research institute. Additionally, by focusing on individuals using public transport or privately owned cars, we attained a representative sample of the general population for which travel sickness is a potential issue and thus can actually give an accurate indication of their susceptibility to motion sickness.

Finally, there is the limitation that a self-report survey does not allow to identify causal mechanisms. While this is less an issue concerning the correlations to gender, age and country, it is more so for the modulating factors and durations. Although the self-indicated exacerbating factors might be correctly identified, experiments would need to be conducted to test these hypotheses.

2.5. Conclusions

With 46% of car occupants having experienced symptoms of carsickness in the past five years, and 59% if including their entire lifespan, it is still a common unpleasant side effect of car travel. Only ships/boats were found more provocative than cars. While busses were associated with similar motion sickness as cars, other modes of transport such as planes, trains, and trams were reportedly less problematic. The cultural (China > other), age (younger > older) and gender (females > males) effects should be taken into account when discussing the relevance of the problem – especially when inferring from specific samples to general conclusions. These effects might also be interesting for the targeted development of countermeasures.

This knowledge on the extent to which passengers of present-day vehicles experience carsickness, and how this is influenced by various non-driving tasks (such as display use) can be used to better understand the possible effect on occupant comfort of autonomous vehicles. While autonomous vehicles could lead to more carsickness due to more people travelling as passengers possibly involving in visual non-driving related activities (Diels & Bos, 2016), knowledge on the current risk factors for carsickness could aid in designing vehicles and driving algorithms that minimize the occupants' carsickness. In the coming decades, gaining control of carsickness might be an important enabler for acceptance of AVs and therefore for leveraging potential positive effects on traffic safety and environmental impacts.

2.6. Appendix

Definitions of Motion Sickness used in Survey:

English: Motion sickness is a condition of feeling unwell which can occur when traveling in anything from ships (seasickness), cars (carsickness), to rollercoasters. Symptoms differ between people but often include fatigue, dizziness, sweating, nausea and eventually vomiting.

German: Bei der Reisekrankheit handelt es sich um ein Gefühl des Unwohlseins, das beim Reisen mit verschiedensten Verkehrsmitteln von Schiffen (Seekrankheit) über Autos bis hin zu Achterbahnen auftreten kann. Die Symptome unterscheiden sich je nach Person. Oft gehören dazu Müdigkeit, Schwindel, Schwitzen und Übelkeit bis hin zum Erbrechen.

Portuguese: Enjoo é uma condição de se sentir mal, que pode ocorrer quando se viaja em qualquer coisa, desde navios, carros, até montanhas-russas. Os sintomas diferem entre as pessoas, mas geralmente incluem fadiga, tonturas, transpiração, náuseas e eventualmente vômitos.

Chinese: 晕动病是指在乘船（晕船）、乘车（晕车）以及坐过山车时感觉不适的状况。症状因人而异，但通常包括疲劳、头晕、出汗、恶心以及最终呕吐。

Chapter 3

Looking forward: in-vehicle auxiliary display positioning affects carsickness

Kuiper, O.X., Bos, J.E., & Diels, C. (2018). Looking forward: In-vehicle auxiliary display positioning affects carsickness. *Applied Ergonomics*, *68*, 169–175.

Abstract

Objective: Carsickness is associated with a mismatch between actual and anticipated sensory signals. Occupants of automated vehicles, especially when using a display, are at higher risk of becoming carsick than drivers of conventional vehicles, as they have a reduced view out of the window. This chapter aimed to evaluate the impact of positioning of in-vehicle displays, and subsequent available peripheral vision, on carsickness of passengers. We hypothesized that increased peripheral vision during display use would reduce carsickness.

Methods: Seated in the front passenger seat 18 participants were driven a 15-min slalom on two occasions while performing a continuous visual search-task. The display was positioned either at 1) eye-height in front of the windscreen, allowing peripheral view on the outside world, and 2) the height of the glove compartment, allowing only limited view on the outside world. Motion sickness was reported at 1-min intervals.

Results: Using a display at windscreen height resulted in significantly less carsickness compared to a display at glove compartment height after 15 minutes of exposure to slalom motion.

Conclusions: Display positioning can modulate carsickness by allowing individuals more outside peripheral vision, increasing the congruence of visual and vestibular sensory information. This knowledge might be used in automotive design to increase passenger comfort by offering general guidelines for display positioning.

3.1. Introduction

Motion sickness can be defined as a state of discomfort caused by real or apparent motion (Reason & Brand, 1975). Signs and symptoms of motion sickness are initially, among other things, (cold) sweating, pallor, burping, salivation, apathy, that may subsequently be followed by nausea, retching and finally vomiting. The occurrence and degree of these symptoms may vary considerably between people, however everyone with a functional vestibular system appears susceptible to motion sickness to some extent (Money, 1970). The underlying mechanism of motion sickness has been theorized to be a mismatch between actual and anticipated sensory signals, typically modulated through visual-vestibular conflicts (Bles et al., 1998; Bos et al., 2008). Alternatively, motion sickness has been proposed to result from postural instability, stemming from sensory information incongruent with how balance is maintained in a natural or known environment (Riccio & Stoffregen, 1991). Therefore, under either theory, *in*congruences in what is seen and (normally) experienced through other senses, such as when below deck at sea, or when reading a book in a car, can *aggravate* motion sickness. Conversely, congruent sensory information, e.g. looking at the earth-fixed horizon when on a moving ship, *alleviates* motion sickness, even when this is presented artificially (Bos et al., 2008; Feenstra et al., 2011; Tal et al., 2012).

Carsickness is a form of motion sickness of which two-thirds of all people have suffered from at some point in their life (Reason & Brand, 1975). Passengers in particular, rather than drivers, become motion sick, even when exposed to identical motion (Rolnick & Lubow, 1991; Dong et al., 2011; Chen et al., 2012). One reason for this is that when controlling a vehicle, motion can correctly be anticipated, reducing the discrepancy between sensed and expected motion. Another, related, reason for the increased risk of motion sickness of passengers is the fact that passengers are not required to have a view out-the-window to operate the vehicle. Restricted vision of the outside world was found to aggravate carsickness (Griffin & Newman, 2004). As opposed to the world outside the vehicle, the vehicle interior moves in conjunction with its occupant, increasing sensory incongruences as more of the visual field is occupied by the vehicle interior. The beneficial effect on motion sickness of out-the-window view holds was found to hold true for both central and peripheral vision independently.

Autonomous vehicles, or rather *highly automated vehicles* (Reilhac et al., 2016), are expected to replace conventional vehicles in the coming decades (see e.g. Litman, 2014). Potential benefits of these future self-driving vehicles are safer roads, reduced traffic congestion, increased fuel efficiency, and time saved by the possibility to engage in non-driving activities (Begg, 2014). However, extensive adoption of self-driving vehicles could lead to increased motion sickness in the general population. Currently, over three quarters of commuters in the US are the sole occupant of their vehicle when getting to work (McKenzie, 2015). This population of drivers will become passengers once automated vehicles are widely adopted. As mentioned, passengers have an increased risk of motion sickness compared to drivers. In addition to this, a key benefit of automated vehicles, i.e. engagement in non-driving activities, may further inhibit passengers' out-the-window view. This, in turn, exacerbates the visual-vestibular mismatch believed to underlie carsickness. However, concept car designs often show sizable, possibly even head mounted, displays to be used for work or entertainment. If engagement in such in-vehicle displays becomes the default state of the occupants of future vehicles, preventing carsickness is expected to become a considerable challenge for vehicle manufacturers. Consequently, display positioning could become a potentially important factor modulating motion sickness in future automated vehicles through influencing available peripheral out-the-window view.

In the present study we therefore aimed to investigate the effect of display positioning on motion sickness in car passengers using an in-vehicle display. We elaborated on an exploratory on-road study (Diels et al., 2016) which included a head-up versus head-down display position. Findings suggested that a head-up display may be able to reduce motion sickness. However, the study suffered from several confounding factors, most crucially the variability in vehicle motions due to the experiment taking place in traffic. For the current study we realized an experiment with reproducible vehicle motion and an hypothesis based on a within-subjects design with two conditions manipulating display position. In one condition the display was at windscreen height (HIGH), and in the other condition at glove compartment height (LOW), the latter offering only limited peripheral vision. The hypothesis tested was that the condition which allowed for more optimal peripheral vision, thus minimal visual-vestibular incongruences, would result in the least motion sickness. To be able to better interpret the main analysis concerning the effect on motion sickness between the two conditions, motion sickness across participants was also analysed both in proportional terms, and in terms of difference in increase in illness over time.

3.2. Methods

3.2.1 *Motion stimulus and test environment*

The study was undertaken using a typical medium-sized estate car (Volkswagen Passat). The vehicle was equipped with an automatic gearbox and cruise control. An accelerometer (Xsens Technologies B.V.) was mounted on the floor of the vehicle behind the front seats. An on-board computer recorded the motion sensor data in conjunction with controlling the task.

For controllability and safety reasons the experiment was realised on a privately owned tarmac road approximately 600 m long, without any other traffic present. Slaloms were driven around markers on the centre of the road 20 m apart, resulting in 13 40 m cycles on the 600 m long track. Each slalom manoeuvre was followed by a U-turn at the end of the track immediately followed by another slalom (see Figure 3.1). Each slalom was driven at a constant speed of 25 km/h using the vehicle’s cruise control.

Following a pilot study exploring the effectiveness of different slalom profiles, we found that a distance of 1 m between the vehicle and the markers at the peak of each lateral motion resulted in a stimulus that was provocative yet not leading to vomiting in a short period of time. As a result, each slalom had an amplitude of 1.5 m and a frequency of 0.16Hz. This frequency in particular has been shown to be most provocative for motion sickness (O'Hanlon & McCauley, 1973). These slaloms were repeated 8 times, lasting 15 minutes in total, including the U-turns. There were two drivers, both of whom had practised driving the slalom at the test track beforehand. Participants were assigned to only a single driver to control for any variation between drivers.

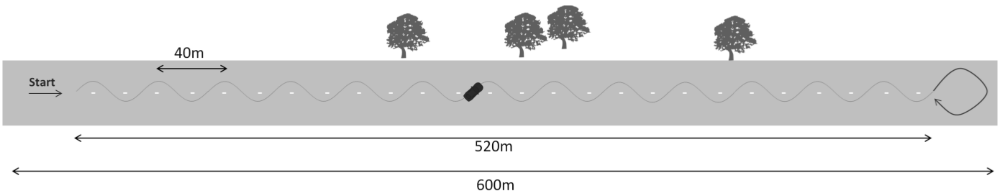

Figure 3.1. Schematic of the test track. The vehicle was driven around 26 markings in slalom driving, corresponding to 13 cycles of 40m. At the ends of the test track there was ample room to do a controlled U-turn. The amplitude of each slalom was 1.5m measured from the markings to the centre of the car. The maximum angle of yaw as seen from the centre-line was about 20°.

3.2.2. Experimental conditions

Two display conditions were realised in otherwise identical circumstances. In the HIGH condition, the display was positioned at eye-height in front of the windscreen, providing considerable peripheral out-the-window view. In the LOW condition, the display was positioned at the height of the glove compartment, offering considerably less view on the outside world as compared to the HIGH condition. The display was pitched to ensure that the viewing angle was equal in both conditions. The seat could be raised vertically to compensate for participant height, keeping the display at eye-height.

3.2.3 In-vehicle display and task

The task was presented on a tablet with an 18 cm (7 inch) screen diameter mounted to the dashboard by the passenger seat in the two possible configurations (see Figure 3.2). The distance to the screen was 60cm, resulting in a FOV of about 15°. The task required constant visual attention, preventing participants from taking their eyes off the display and thus influencing their available peripheral vision. The task itself was an adaptation of the SuRT task (SuRT, ISO14198, 2012) and consisted of a continuous series of trials over the entirety of each of the 15-minute conditions. In every trial a static grid of 36 arrows was presented with arrows pointing down, left, or right. In half of the trials a single arrow pointing up was present. The participant was instructed to push a 'yes' button on a hand-held box when an up-arrow was identified, and a 'no' button when the upward pointing arrow was absent. After responding, the next grid was immediately displayed regardless of response given, to keep the participant engaged. If within 3 seconds no button was pressed, a fixation cross was presented for 1s to indicate a miss, immediately followed again by the next trial. No other feedback on task performance was given. Participants were instructed to keep their visual attention on the task throughout the experiment and to keep their head in approximately the same position (i.e. "don't make large adjustments in posture during the experiment").

Figure. 3.2. The two variations of display positioning used in this experiment, HIGH (left) and LOW (right).

3.2.4 Motion sickness measures

During each 15-min condition, participants provided self-ratings of their motion sickness severity at 1-min intervals as indicated by an auditory beep, using an 11-point misery scale (MISC, table 3.1, Bos et al., 2005). The scale exploits the knowledge that all motion sickness symptoms other than nausea, retching and vomiting may vary between participants, but, if present, these symptoms normally precede the latter. A MISC of 6 or higher (i.e., any nausea), was taken as a criterion to terminate a running condition so as to allow participants to recover in between conditions and minimising cross-over effects. If a condition had to be stopped due to nausea, the last reported MISC rating was conservatively assumed for the remaining measuring moments, thus preventing missing values and facilitating the statistical analysis.

Table 3.1.
11-point MIsery SCale (MISC) (Bos et al., 2005)

Symptoms		Misc
No problems		0
Some discomfort, but no specific symptoms		1
Dizziness, cold/warm, headache, stomach/throat awareness,	Vague	2
sweating, blurred vision, yawning, burping, tiredness,	Little	3
salivation, . . . but no nausea	Rather	4
	Severe	5
Nausea	slight	6
	fairly	7
	severe	8
	(near) retching	9
Vomiting		10

3.2.5 Procedure and Participants

Approval by the TNO Human Factors institutional Review Board on Experiments with Human Subjects was obtained in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. Candidate participants which indicated they had never suffered from motion sickness in any mode of transport for the last five years were not considered for this experiment. All participants included were free of vestibular disorders as known by themselves, and had not been drinking alcoholic beverages during 24 hours in advance of the experiment. Also they were informed about the purpose and procedures of the experiment and signed an informed consent prior to the first experimental condition. A total of 18 participants, 8 males and 10 females, participated in this study. Ages ranged from 19 to 33 years with an average of 26 ± 4.6. Participants alternated in couples with respect to the two conditions realised, allowing them a pause in between the two conditions of approximately one hour. Prior to the experiment the MISC-scale was explained to the participant in conjunction with the task instructions, and then again at the start of each condition to ensure retention. The experimenter controlled the vehicle while the participant took place on the passenger seat with the display in front of them. Anticipating the first condition, participants practiced the task until it was clearly understood. Before each condition, participants reported their initial MISC. An MISC of 2 or up (i.e. any symptoms) at the start of a condition was considered undesirable and would therefore lead to exclusion. The conditions were counterbalanced between participants to prevent order effects.

3.2.6 Statistical methods

To quantify the variability in slaloms driven, a power spectral density analysis was performed on the lateral acceleration data, yielding both peak frequency and RMS acceleration amplitude. Paired t-tests were used for accelerometer data and task scores. Parametric repeated measures ANOVA was used with MISC ratings as the dependent variable. Three factors were included: condition, time and participant. Participant was included as a random factor. To visualize inter-individual differences we used linear regression slopes for each participant per each condition, and compared these with a paired t-test. Statistical data analysis was performed using R (Version 3.3.1). Averages are reported along with their standard deviations. Due to incidental conditions, among which an initial MISC ≥ 2, data from three participants were excluded. Data analysis was subsequently performed on data from 15 participants.

3.3. Results

3.3.1 Motion profiles

A power spectral density analysis of the lateral acceleration sensor data revealed an average peak slalom frequency of 0.161 Hz ± 0.01. Therefore, the frequency variability between conditions and participants was about 6%. There was no significant difference between the two conditions in terms of peak frequency ($t(24) = 0.547$, $p = .590$). Average RMS of lateral acceleration was 1.12 m/s^2 ± 0.14, meaning the amplitude variability across all participants and conditions was about 13%. The RMS of lateral acceleration did not significantly differ either between conditions ($t(24) = 0.431$, $p = .670$).

3.3.2 Motion sickness scores

The average illness rating after 15 minutes was 2.0 ± 2.10 in the HIGH-display condition, and 2.8 ±1.81 in the LOW-display condition. This corresponds to a 43% reduction of illness scores. Figure 3.3 shows the illness ratings of participants for the two conditions over the entire 15-minute period. A repeated measures ANOVA showed a significant increase in score over time for both conditions ($F(1,14) = 32.69$, $p < .001$, partial $\eta^2 = 0.578$). A significant effect of condition on illness scores was also found ($F(1,14) = 5.012$, $p = .042$, partial $\eta^2 = 0.264$). Regression lines (as also shown in Figure 3.3) were derived from the LOW ($F(1,238) = 67.580$, adjusted $R^2 = 0.218$, $p < .001$) and the HIGH ($F(1,238) = 55.499$, adjusted $R^2 = 0.186$, $p < .001$) subsets of the data. These regression lines also significantly differed, $F(1,476) = 8.164$, $p = .004$. This was analysed by using a dummy variable for the HIGH/LOW conditions, and examining the interaction effects of the linear model.

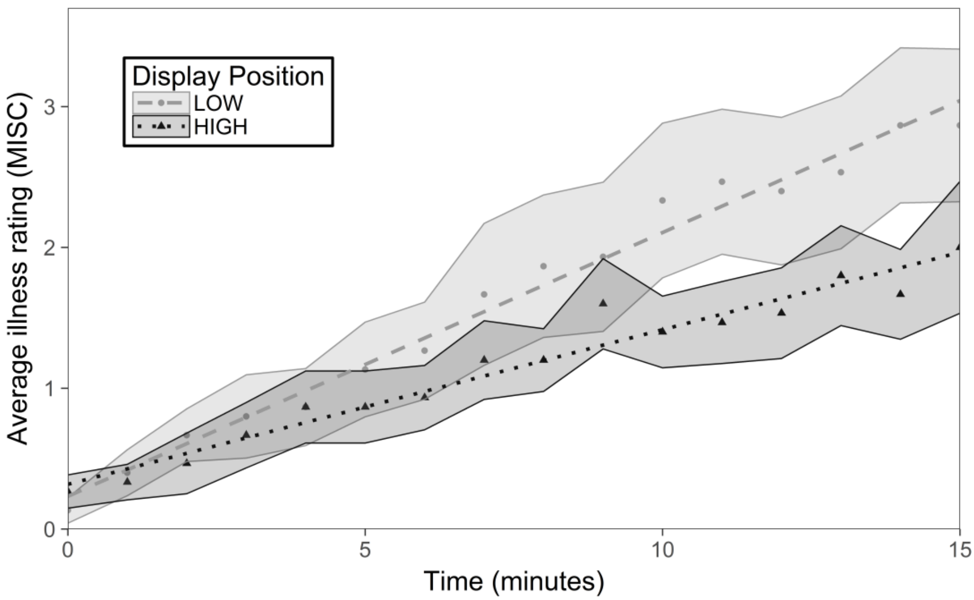

Figure 3.3. Average illness ratings over time for the LOW and the HIGH condition. Grey areas depict SEM.

An alternative way to explore the data, rather than examining average scores, is to look at the percentage of participants over time that reached certain thresholds of illness rating (MISC). In motion sickness studies, often a portion of participants show no effect to the provocative stimulus (see e.g. Dong et al., Perrin et al, 2013). This can also be seen in Figure 3.4. Each line represents the proportion of participants that reached a certain illness rating at that time of measurement. Note that a MISC of 1 is "*some discomfort, but no symptoms",* and was therefore sometimes scored at the beginning of a drive. As can be seen from the top most lines in the graph, the proportion of participants that scored a MISC of at least 1 increased at roughly the same rate in both conditions. However, looking at the development of further symptoms, as can be seen in the lines for the MISC reaching 3 or higher and 5 or higher, the two conditions differ.

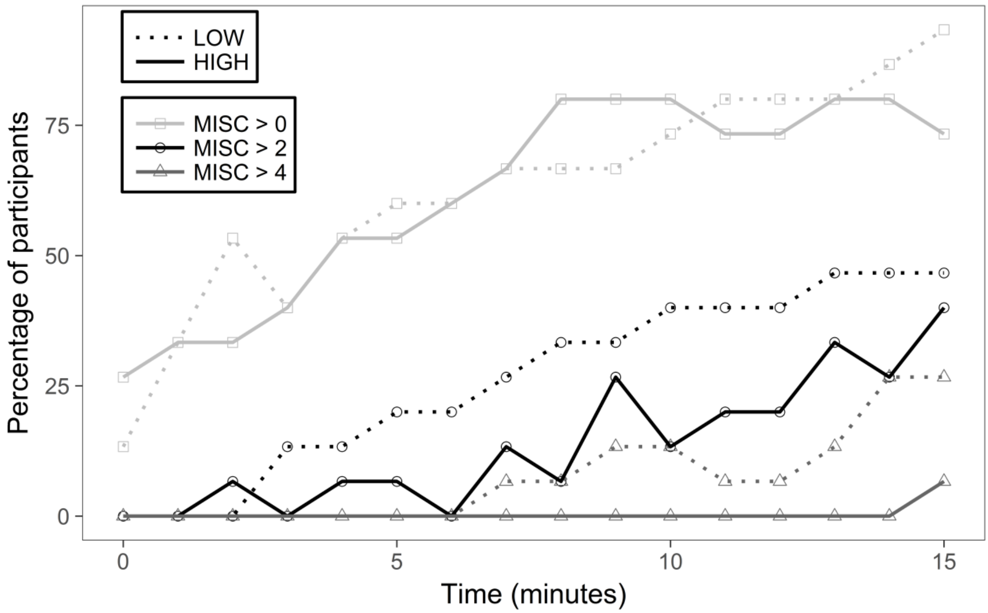

Figure 3.4. Percentage of participants over time that attain at least a certain illness score (MISC). Both conditions illicit a similar response in terms of initial rise in MISC (the lines using squares). However once this threshold of a MISC of 1 is reached, the LOW condition illicits a larger effect, as indicated by a higher proportion of elevated MISC scores.

To further explore the differences between conditions within participants we used an additional analysis. For each participant two regression lines, one for each condition, were calculated. For each regression line, the intercept was fixed at the initial illness score at $t=0$. The average adjusted R-squared of the regression lines was 0.776 ± 0.249. The values of the slopes of these regression lines, i.e. the fitted amount of increase in MISC score per each unit of time, are shown in Figure 3.5. A paired t-test showed these regression slope values differ significantly between the HIGH and LOW condition, $t(14) = 2.771$, $p = .015$.

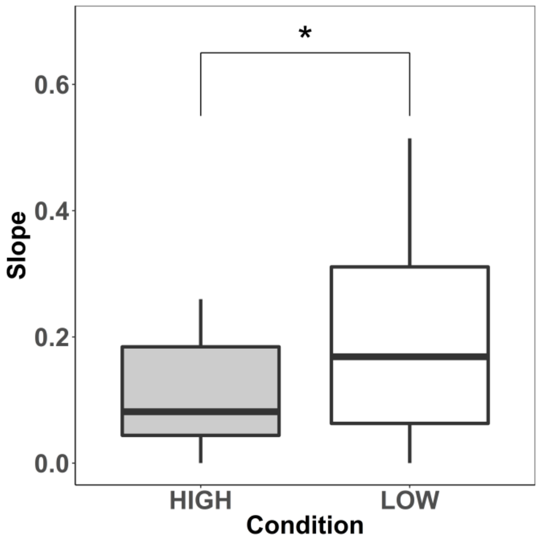

Figure 3.5. A regression line for each condition (HIGH/LOW) and each participant was calculated. Boxplots show the slopes of these regression lines.

3.3 Task performance

We analysed task performance to assess whether participants consistently attenuated to the task across the two conditions. On average, participants scored 90.5% (± 5.1%) of the trials on the search task correct, with 9.5% incorrect or late answers. There was no significant difference between the two conditions in terms of task performance (paired t-test $t(12) = -0.41494$, $p = .686$). Average reaction times were slightly lower for the HIGH condition with 1.25 (±

0.26) seconds on average compared to 1.32 (± 0.24) seconds for the LOW condition. However, this difference was also not significant (paired t-test $t(12) = 1.2136$, $p = .248$).

3.4. Discussion

In this study we examined the level of carsickness in front seat passengers performing a visual search task using a display positioned at 1) eye-height in front of the windscreen (HIGH), providing considerable peripheral out-the-window view, and 2) at the height of the glove compartment (LOW) offering considerably less peripheral vision. In line with the hypothesis that increased peripheral vision reduces carsickness, the HIGH display position was indeed found to lead to significantly less motion sickness compared to the LOW display position.

Our findings are in line with other studies showing the beneficial effect of enhanced peripheral vision on carsickness. For instance, Probst and colleagues (1982) also found that out-the-window view led to significantly reduced motion sickness compared to viewing an artificial static visual field (a map) located on the passengers' laps. A study by Turner and Griffin (1999) showed a correlation of motion sickness and seating position in coach passengers which was attributed to differences in forward vision as a function of position. Similarly, Griffin and Newman (2004) showed in multiple experimental conditions that out-the-window view significantly reduces motion sickness, especially when this view contains information about the trajectory of the vehicle. Perrin and colleagues (2013) found that professional rally co-drivers reported increased motion sickness when taking notes during course reconnaissance, reducing out-the-window vision. These studies, expanded upon by our findings of reduced motion sickness with increased peripheral vision, underline the importance of the relationship between vision and carsickness. The findings of Diels and colleagues (2016) found a similar effect as our study, with a head-up display leading to a reduced incidence of motion sickness. Our congruent data substantiates the findings of that exploratory study. In addition, their findings are in support of generalizability of our findings, namely that the effect of display position may hold under car motion in natural traffic rather than only during slalom driving. While the design of this study did not allow to investigate underlying (neural) mechanisms of carsickness, results of the present study reaffirm the importance of vision on carsickness.

Having a completely unobstructed view on the earth-fixed world around the vehicle is the quintessential way to reduce motion sickness following visual-vestibular incongruences. However, with limited vision, motion cues can still be inferred from both foveal and peripheral vision. While the *peripheral dominance hypothesis* (Dichgans & Brandt, 1978) has been nuanced, peripheral vision is still regarded as being paramount in self-motion perception (Webb & Griffin, 2003; Bardy et al., 1999; Warren & Kurtz, 1992). Self-motion perception is principally related with *vection*, which is the perceived sense of self-movement (Palmisano et al., 2015). It is *vection*, rather than simply optic flow, that is assumed to play a major role in motion sickness in which a visual component is involved (Stern et al., 1990; Keshavarz, et al., 2015). Thus, when central visual information is restricted (e.g. when working on a screen), peripheral vision is a central factor modulating motion sickness mediated through its role in self-motion perception, as also evident in the present study. However, researchers on carsickness should be aware not to fixate on a single aspect, such as peripheral vision, given that nuances in the visual scene during motion -or even optic stimuli by themselves- cause or can modulate motion sickness in a complex and multifaceted fashion (So & Ujike, 2010; Bos et al. 2010; Kennedy et al., 2010).

A factor that might be thought to have impacted the participants' sickness in this study is the voluntary or inattentive head orientation of participants. Namely, we did not restrain the head of participants, but rather left them free to orient their head in any position. Besides the instruction to try to keep their focus on the display, and not to drastically alter their posture, no other instructions were given. However, the slalom motion we utilized exposed participants predominantly to lateral linear motion, and to our knowledge there is no evidence in the literature which suggests that the otoliths, the vestibular organs sensitive to lateral linear acceleration, function differently under different head orientations. The semi-circular canals, sensitive to angular motion, receive equal stimulation regardless of head tilt. In addition, a study by Wada and Yoshida (2016) found vision is the predominant factor affecting carsickness even with a head tilt of 20° against baseline. Therefore, we do not expect head tilt to have had a large impact on eventual motion sickness compared to the effect of vision.

In this study, sickness sores after 15 minutes of exposure did not lead to excessively high sickness scores, on average 2.0 and 2.8 for the HIGH and LOW condition, respectively. This was however anticipated. Motion sickness is a process over time, typically increasing monotonically during the first 60 minutes of consistent motion exposure (McCauley et al., 1976). As also evident in our findings, prolonged exposure to motion has an additive effect on the severity of sickness. We selected the motion stimulus with the goal to invoking a response in the majority of participants while preventing unnecessary discomfort. Our data was best modelled by a linear fit, implying prolonged exposure to the stimulus would have led to increasing motion sickness scores and continued differentiation between the two conditions. However, it must be noted that a comprehensive model of motion sickness over time could not be strictly linear, given the upper limit of the scale being a maximum score of 10 (defined as vomiting). However given the present data and the knowledge of the monotonic rise of motion sickness given continuous stimulus, there is good reason to assume average sickness scores would have continued to rise after the 15 minute duration.

A different factor that may have somewhat dampened our motion sickness levels was participants' continuous engagement in a (mentally) distracting task (i.e. visual search task) which has previously been shown to reduce motion sickness (Bos, 2015). Given the task's demanding nature, requiring continuous attention as substantiated by consistent scores across participants, it most likely diminished overall sickness scores in this experiment. However, since the principal aim in this study was to investigating the effect of peripheral vision, a method demanding continuous visual attention was required to ensure the participants' gaze remained on a display. This necessitated inclusion of the task in our design. Given the confounding nature of the illness reporting procedure, no conclusions concerning the effect of motion sickness on task performance can be drawn. Finally, a factor influencing motion sickness, was that the slalom used for controllability is by definition a predictable motion, which reduces sickness (Rolnick & Lubow, 1991; Dong et al., 2011). This implies that natural vehicle motion of similar intensity rather than a repetitive motion would be expected to result in higher sickness levels.

Since the inception of automobile travel, the subject of carsickness has received only limited attention among scientists. More surprising is that despite the recent substantial attention for self-driving vehicles, carsickness in automated vehicles has received equally limited attention, although various authors established that carsickness might be a serious issue in self-driving vehicles (Diels, 2014; Diels & Bos, 2015; Sivak & Schoettle, 2015; Diels & Bos, 2016). However, the public's acceptance of automated vehicles, despite the plethora of advantages they offer, might be seriously impeded if carsickness proves to be a serious issue. Concept cars often show designs where emphasis is put on use of in-vehicle displays and the ability to rearrange seats to create a more 'living-room like' experience. However, further reducing external and forward vision of passengers (Griffin and Newman, 2004), such as through backward facing seats or even head mounted displays, will further exacerbate the risks at carsickness. While self-driving vehicles do not need windows to operate, it is imperative to focus on the passengers' comfort experience which suggests that windows are here to stay.

In addition to comfort, carsickness may also have implications for driver safety. Following the Society for Automotive Engineers taxonomy (SAE, 2014), current production vehicles with e.g. lane-keeping assistance and adaptive cruise control offer level 2 automation. Full door-to-door automated driving would constitute level 5 automation. In the intermediate phases the vehicle's occupant will be able to engage in other activities but has to be able to take back control of the vehicle in a limited timeframe. This *transfer of control* has already been the focus of several studies concerning envisaged safety risks. Delayed or reduced situation awareness, potential drowsiness, and distraction from engagement in non-driving activities can have a detrimental effect on the ability to operate a vehicle after a period of inactivity (Vlakveld, 2016). Research into transfer of control should include motion sickness as a factor of interest in addition to these factors, since even mild motion sickness is known to reduce task performance (Rolnick & Bles, 1989; Bos, 2004). When passengers with restricted vision in automated vehicles are exposed to provoking vehicle motion (e.g. windy roads, repeated lane changes or inner city traffic), their take over and subsequent driving abilities may be compromised due to motion sickness.

As stated before, a better view-out-the window reduces carsickness since it provides an earth-fixed reference frame congruent with the vehicle's motion. While non-visual means of counteracting motion sickness (Keshavarz & Hecht, 2014) might be feasible in cars, the effect of vision in carsickness is better understood. Interestingly, the beneficial effect of vision has been shown to be remain when this visual information is presented artificially (Bos et al., 2008; Feenstra et al., 2011; Tal et al., 2012; Kato & Kitazaki 2008; Miksch et al., 2015). For instance, Feenstra and colleagues (2011) showed that the addition of earth-fixed reference points in a flight simulator going through predetermined motions could reduce motion sickness by 50%. Participants in this study were not told about the nature of the earth-fixed reference points, demonstrating that such artificial stimuli can be intuitively beneficially. When adding an anticipatory future motion trajectory the reduction in motion sickness was up to 80%. Utilizing similar artificial presentations of an earth-fixed reference frame and future motion trajectories could provide effective means to reduce carsickness in automated vehicles. However, more research is needed to assess the feasibility of this technology on the road, rather than in a simulator.

This paper aimed to reaffirm the general importance of vision on carsickness, and specifically to quantify the effect of display positioning on carsickness. The results found here aid in further understanding the functional role of peripheral vision out-the-window in carsickness. Additionally, this study contributes practical knowledge that can be used in automotive design to increase passenger comfort by offering an elementary guideline for display positioning. Looking forward into the future, passengers of self-driving vehicles will expectedly be exposed to a vastly different visual scene than occupants of vehicles today, with engagement in displays being a central aspect of this shift. This expected change in the general passengers' visual landscape adds to the importance of further research on the subject of carsickness.

Chapter 4

Complexity of artificial visuals: vection does not necessitate visually induced motion sickness

Kuiper, O.X., Bos, J.E., & Diels, C. (2019). Vection does not necessitate visually induced motion sickness. *Displays*, 58, 82–87

Abstract

Objective: Vection, i.e. a visually induced illusory sense of self-motion, is assumed to play an essential role in visually induced motion sickness (VIMS). However, its precise role is unknown. Following the sensory conflict theory, a constant state of vection is not expected to lead to a visual-vestibular conflict whereas variability in vection, i.e. change in vection strength over time, would.

Methods: In this study we investigated whether variability in vection rather than vection caused VIMS in participants exposed to constant optic flow using a head-mounted display.

Results: Strongest possible vection (i.e. 100% on a 0-100% scale) was reported by 16 out of 18 participants at some point during the experiment, with a total average vection score over the experiment of 58.6%. Initial motion sickness symptoms were reported by 15 out of 18 participants, although only averaging 1.78 on an 11-point scale. Neither average vection strength nor variability in vection were significantly correlated with motion sickness.

Conclusions: Relating our findings to the literature, we argue that vection should be understood not as a direct cause of VIMS, but as a perceptual state still depending on other visual factors before VIMS occurs. Vection by itself, even if it is experienced strongly, does not necessitate VIMS. Our findings corroborate observations reported in the literature that vection is a highly complex, multifaceted phenomenon and is not yet fully understood in its relation to motion sickness.

4.1. Introduction

Visually induced motion sickness (VIMS) is a type of motion sickness caused exclusively by visual motion rather than by physical motion. Its symptoms are, besides added oculomotor disturbances, principally the same as that of general motion sickness: pallor, cold sweat, dizziness, fatigue, nausea, potentially culminating in vomiting (Stanney & Kennedy, 1997; Golding & Gresty, 2015). While the relation between physical motion and motion sickness is relatively well understood (Reason & Brand, 1975; O'Hanlon & McCauley, 1974; Bos & Bles, 2002), the root cause or causes of VIMS in particular are not fully understood (Kennedy et al., 2010; Hettinger, 2002; Keshavarz et al., 2014, 2015). The principal framework in which motion sickness is most commonly explained is the sensory conflict theory (Reason & Brand, 1975; Reason, 1978; Oman, 1982, 1990; Bles et al., 1998; Bos et al., 2008). This theory stipulates that a mismatch between sensed and expected motions is the origin of motion sickness, often resulting from discrepancy between visual, vestibular, and/or the proprioceptive sensory information. The relationship between physical motion and how it results in motion sickness has been studied extensively and produced predictive models (e.g. ISO 2631-1, 1997). Exactly how moving visual scenes lead to motion sickness is less well-understood.

When an observer is stationary and visual motion is presented, this does not always lead to VIMS. Generally, VIMS is assumed to only arise when the observer experienced *vection*, an illusory sense of self-motion brought on by visual cues (Palmisano et al., 2015). However, while vection seems to be *necessary* for VIMS to occur, it has not been found to be *sufficient.* That vection plays an important, but ultimately non-decisive role in VIMS is reflected in the literature on this subject. For instance, many studies find a strong relation between vection and VIMS (Hettinger et al.,1990; Smart et al., 2002; Palmisano et al., 2007; Diel & Howarth, 2011). On the other hand, however, several studies find vection occurring without leading to VIMS (Prothero, 1999; Webb & Griffin, 2002, 2003) While vection is generally the focus of VIMS research, various authors have questioned what to make of the ambiguous relationship vection has with VIMS (Keshavarz et al., 2015).

An explanation for why vection is not consistently found to lead to VIMS already exists in the sensory conflict theory. Namely, vection by itself does not necessarily lead to a conflict between expected and sensed motion. A steady state of vection, i.e. constant vection strength over period of time, suggests a constant speed of self-motion, which does not lead to an expectation of vestibular response since the vestibular organs are only sensitive to *accelerations* and not to constant velocity. Rather than vection per se, only *variability in vection*, i.e. change in vection strength over time, suggests changes in velocity of self-motion and would produce a visual-vestibular conflict in a stationary observer. This point, that changes in vection might be the decisive factor in VIMS, has been explicitly raised by only a few authors (Nooij et al., 2017; Bonato et al., 2008).

In fact, Bonato et al. (2008) found evidence for the hypothesis that variations in vection rather than only vection underlie VIMS. In their study, the authors presented participants with an alternating optic flow pattern in one condition, and a constant optic flow pattern in the other, and found that the alternating optic flow condition lead to lower average vection but increased variability in vection, and significantly higher reported VIMS. These findings further substantiate the premise that vection does not have a simple relation to VIMS. However, the use of two different conditions of optic flow does not rule out that the effect on VIMS was not directly a result of variability in vection. Rather, the condition of alternating optic flow could have simply constituted a more provocative stimulus independent of its effect on vection, for instance by increasing the visual-vestibular conflict.

Therefore, in this experimental study, we also aimed to answer the question whether it is vection, or rather *variability in vection* that leads to VIMS. Importantly, we opted to use a single constant optic flow stimulus to investigate exclusively the effect of variability in vection on VIMS, without altering optic flow. Due to the fact that under constant optic flow vection is experienced variably (Seno et al., 2017) a constant optic flow pattern was expected to equally lead to a usable measure of variability in vection in participants, without introducing cofounding factors relating to changing the optic flow. Based on the sensory conflict theory, under which variable vection is theorized to lead to the increased visual-vestibular conflict, we expected to find a stronger (and significant) correlation between alterations in vection and VIMS as compared average vection strength and VIMS.

4.2. Methods

4.2.1 *Participants*

Eighteen volunteers participated in the experiment (10 males, 8 females, mean age 25.2 ± 3.6). All had normal or corrected to normal vision and indicated to be free of vestibular problems.

4.2.2 *Stimuli and Apparatus*

The stimulus pattern consisted of an array of white spheres against a dark background displayed using a HTC Vive head mounted display (HMD). The resolution per eye was 1080 by 1200 pixels with a refresh rate of 90Hz. The full horizontal and vertical field of view were 110 degrees, approximately 90 degrees horizontal for each eye. The white spheres were modelled in the game engine Unity (version 5.6.1f1), and appeared in a semi-random pattern at the maximum viewing distance, going in a straight line towards the anterior-posterior plane of the participant (see Figure 4.1). All spheres moved in unison in terms of speed and position relative to each other in the virtual environment for the full duration of the experiment. Each individual sphere was in view for approximately seven seconds. When looking forward, as was explicitly instructed to the participant to ensure a similar exposure to the stimulus, participants viewed a radially expanding optic flow pattern suggesting forward motion. The HMD corrected for head movements to ensure the stimulus always appeared moving along an earth-fixed (rather than an observer-fixed) trajectory.

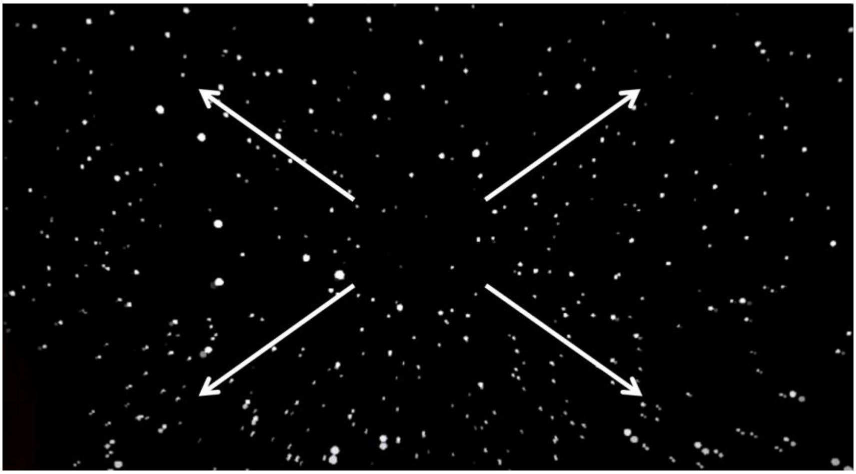

Figure 4.1. The stimulus pattern used in the experiment. In the 3D environment the white spheres steadily moved in a straight lines towards the anterior-posterior plane of the participant, resulting in radially expanding optic flow suggesting forward motion.

4.2.3 *Measurements*

Before and after exposure to the VR stimulus, participants filled out the Simulator Sickness Questionnaire (SSQ, Kennedy et al., 1993) and indicated their motion sickness score on the 11-point Misery Scale (MISC, Bos et al., 2005), see table 4.1. Both these methods give an indication of motion sickness and are commonly used in studies concerning motion sickness, while the SSQ also subdivides nausea or oculomotor related discomfort and disorientation. In addition, before the experiment participants filled out the Motion Sickness Susceptibility Questionnaire (MSSQ, Golding, 2006), in order to assess their susceptibility to motion sickness compared to the expected average susceptibility of a representative sample.

Table 4.1. 11-point MIsery SCale (MISC) (Bos et al., 2005)

Symptoms		Misc
No problems		0
Some discomfort, but no specific symptoms		1
Dizziness, cold/warm, headache, stomach/throat awareness,	Vague	2
sweating, blurred vision, yawning, burping, tiredness,	Little	3
salivation, . . . but no nausea	Rather	4
	Severe	5
Nausea	slight	6
	fairly	7
	severe	8
	(near) retching	9
Vomiting		10

To measure vection during the experiment, we constructed a simple hand-held device with a single continuous slider. The position of the slider corresponded linearly to a signal in the range of 0-100 (percent) that was logged at 10Hz via USB in the same computer program that ran the stimulus. Participants were asked to report vection throughout the full ten minutes of the experiment. Prior to the experiment, participants were explained the concept of vection. When explaining use of the device to indicate vection, the extremes of the slider were explained as "0%: I have no sensation of moving myself, but rather the objects are moving around me" and "100%: I have the sensation I am moving past the objects, which are standing still". Therefore, a score of 0% indicated a complete absence of vection, while a score of 100% indicated the strongest possible vection. Participants were told they should, at each moment for the full duration of the experiment, indicate their experienced vection on a continuous scale, i.e. they could indicate any percentage spanning the two extremes. For instance, if the participant positioned the slider halfway (at 50%), this implied the participant experienced both self-motion and approximately equally strong motion of the environment. The average vection score was calculated simply by the average score over the ten minutes.

Vection variability score was calculated by using the sum of the absolute of differences between each sample of vection data over the 10 minutes, analogous to path length. For example, if vection score during the 10 minutes would only rise monotonically from no vection (0%) to the strongest possible vection (100%), and then monotonically decreases back to no vection (0%), this would entail a total vection variability score of 200% (assuming no other slider input was given during the 10-minute period). This method to calculate vection variability has the advantage over common measures for variation (e.g. standard deviation) in that increased change in vection response actually substantiates a higher score. For example, in the case of standard deviation a single reported change in experienced vection halfway through the experiment from no vection (0%) to complete vection (100%) would lead to the absolute maximum possible standard deviation score, while only a single change in experienced vection occurred. Conversely, the vection variability score we utilized we believe provides a better measure for of changes in vection over time, without adding much complexity.

4.2.4 *Procedure*

Approval by the Ethics Committee of the Faculty of Human Movement Sciences of the VU University was obtained in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. Before the experiment, participants were informed about the experiment and signed the informed consent form. Subsequently, they filled in the MSSQ, SSQ and indicated their MISC score as a baseline. Participants were handed the vection indicator device and were instructed to demonstrate the use of the device by indicating what the response should be either for complete vection (100%), or no vection at all (0%); this was done to ensure participants had a feel for the device since they had no visual feedback during the experiment once they put on the HMD. Participants put on the HTC vive, and were allowed to adjust the head mounted display until they indicated it was comfortable and they had sharp vision on a simple wireframe representation of the room, before the display was set to black again. Once the participants indicated they were ready to start, white noise was played over the headphones and the stimulus was initiated. After ten minutes, the stimulus and white noise stopped and participants were helped with taking off the head mounted display. Directly after taking of the HMD, participants again filled out the SSQ and reported their MISC score.

4.3. Results

All subjects were able to complete the experiment. Maximum possible vection, i.e. 100%, was reported by all but two participants at some point during the 10 minute exposure. On average, vection scores were 58.6% ± 29.6%. MSSQ scores were on average 13.53 ± 13.45, which falls between the 50th and 60th percentile in term of motion sickness susceptibility (Golding, 2006).

Reported motion sickness after the experiment was on average 1.78 ± 1.06 on the MISC scale, with on average 18.7 ± 10.1 for the SSQ total scores. The SSQ subscales showed on average 9.68 ± 8.14 *Oculomotor*, 21.7 ± 18.6 for *Disorientation*, and 10.6 ± 12.6 for *Nausea*. These reported scores correspond to 15 of the 18 subjects indicating an increase in MISC after the experiment. On the SSQ, 17 of 18 participants reported increase in at least one symptom. The two scales for motion sickness showed a strong correlation, $r = .753$, $p < .05$. The various sub-items of the SSQ did not significantly differ from the main SSQ score ($p > .05$), thus we opted to use exclusively the MISC scores as main indication of motion sickness occurrence in this study.

Variability in vection, as calculated by the total sum of the absolute changes over the 10 minutes, was on average 912.1% ± 595.1%. Some participants showed comparatively constant levels of vection, while others displayed clear alterations over time. This can also be seen in Figure 4.2 which shows the reported vection over the 10 minutes for four different participants for illustration purposes.

A Pearson product-moment correlation coefficient was computed to assess the relationship between vection and motion sickness. We found no correlation between vection and sickness scores, $r = -.28$, $p = .238$. We also did not find a correlation between variability in vection and sickness scores, $r = .19$, $p = .451$. See Figure 4.3 for a scatterplot of motion sickness against both vection and vection variability.

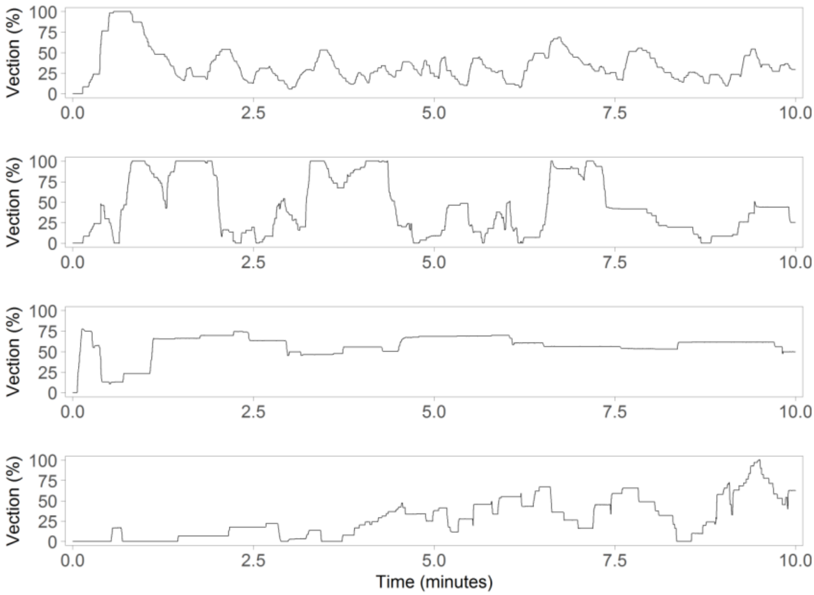

Figure 4.2. Vection response (as given by the hand-held device) over the 10 minute experiment of four typical participants. Some show large alterations in vection over time (e.g. 2nd from the top), while others are more constant in their perceived vection (e.g. 3rd from the top).

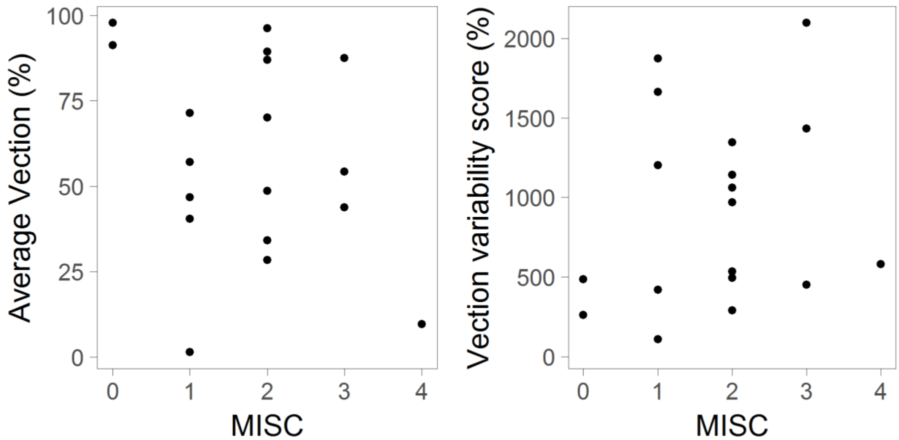

Figure 4.3. *Left:* Average vection scores over the 10-minute experiment plotted against MISC scores. *Right:* Variability in vection, as calculated by the sum of the absolute differences over the 10-minute experiment, plotted against MISC scores.

4.4. Discussion

The stimulus we used was effective in inducing vection. Strongest possible vection (i.e. 100% on a 0-100% scale) was reported by 16 out of 18 participants at some point during the experiment, with a total average over the experiment of 58.6%. MSSQ scores indicated participants were of averagely susceptible to motion sickness (Golding, 2006). The majority of participants indicated initial symptoms of motion sickness, albeit mostly mild symptoms (i.e. average MISC of 1.78 after the 10 minute exposure); none of the participants experienced nausea at any point. Contrary to our expectations, we did not find vection scores and VIMS to be related, nor did we find variability in vection and VIMS to be related.

While the present study was not the first that did not find a relationship between vection and VIMS (Prothero et al, 1999; Webb & Griffin, 2002, 2003), we did expect to find evidence that variability in vection underlies VIMS, as was found by Bonato and colleagues (2008). Similar to our findings, a study by Nooij and colleagues (2017) investigated variability in vection as a probable cause for VIMS and also found no indication that variability in vection underlies VIMS. In their study however, the authors did find a significant positive relationship between vection and VIMS, but acknowledge no clear-cut answers to exactly how vection and VIMS are related exist at this point. A possible explanation why Bonato and colleagues (2008) found an increase in VIMS with increased variability in vection is that the alternating optic flow condition used by these authors not only lead to increased variability in vection, but also influenced additional factors, e.g. a frequency dependent (Diels & Howarth, 2013) visual-vestibular conflict, leading to VIMS.

An aspect not often mentioned that might complicate determining the relationship between vection and VIMS is participants' interpersonal differences in terms of visual dependency. Individuals that score higher on the rod-and-frame test are shown to be more susceptible to simulator sickness (Barrett & Thornton, 1968). Furthermore, higher field dependence, as measured by the rod-and-frame test, has been shown to modulate vection scores depending on the method of presentation of the vection stimulus (Keshavarz et al., 2017). These findings suggest that individuals experiencing vection might not necessarily weigh visual information equally, and therefore not have a similar perceptual visual-vestibular conflict potentially causing motion sickness, even despite similar motion sensation. Further complicating vection research is the fact that vection is not a concept participants are familiar with, and researchers have not always utilized a consistent definition (Keshavarz et al., 2015). In the present study, therefore, we aimed to provide all participants with a thorough and consistent explanation of vection to ensure they understood the concept.

An additional conceptual framework, building on the sensory conflict theory, to understand vection and (visually induced) motion sickness has been proposed in the form of resting frame information (Prothero, 1998; Prothero et al., 1999). In this theory the 'rest frame' is the reference frame utilized by the central nervous system for spatial judgements, i.e. the frame perceived as stationary. Vection could lead to conflicting information on what is the correct rest frame, leading to VIMS. This theory can explain how strong vection, or even alterations in vection, does not necessarily lead to a larger conflict and subsequent VIMS, as long as the assumed veridical resting frame remains consistent. A second, associated, perspective on the potential principal component in VIMS is a different form of frame information, namely frame in terms of orientation. For orientation in space not only visual motion, but also frame information –i.e. horizontal and vertical lines– and polarity –i.e. objects suggesting the direction of the orientation of the true gravitational vector– are important (Howard & Childerson, 1994). However, the relative importance of various visual cues in determining orientation and self-motion is not fully understood. While visual stimuli such as the one used in the present experiment might be potent in influencing perception of motion, frame orientation information is absent. Vection could potentially be a separate phenomenon from the loss of orientation, caused by specific aspects of a visually ambiguous scene. An incongruence in the subjective vertical, i.e. loss of orientation in respect to one's orientation to gravity, has been theorized to be the principal component in motion sickness (Bos et al., 2008; Bos & Bles, 1998) If loss of orientation to vertical is the main factor in VIMS, rather than vection, this might explain why vection is sometimes found in the absence of VIMS. This hypothesis could be tested by comparing vection stimuli, and finding one stimulus that does not lead to VIMS but incites clear vection, and another stimulus that does lead to VIMS under equal levels of vection in the same participants.

The existence of vection without VIMS we found can be further potentially explained by the abstract stimulus we used. While background motion can facilitate VIMS (Lubeck et al., 2015), our stimulus did not suggest a coherent background, but rather only incrementally more distant independent objects. In addition, the virtual objects we utilized, abstract geometric spheres, made estimation of what their actual velocity was impossible. There is evidence that humans are already poor in general at estimating velocity from exclusively visual cues (Monen & Brenner,1994), and that rather use mainly physical cues to estimate velocity (Harris et al, 2000). Furthermore, it has been suggested that abstract stimuli might reduce the believability of motion stimuli, subsequently influencing how provocative these stimuli are in terms of inciting motion sickness (Diels & Howarth, 2011). These combined factors, i.e. ambiguities of the stimulus used, might explain how, while self-motion was experienced, in our experiment the actual neurological conflict underlying motion sickness might have been reduced, subsequently leading to low VIMS scores. Possibly a process of quarantining of abstract stimuli plays a role (Gresty et al., 2003).

Considering the relatively high scores for vection we found, motion sickness scores we found were low when compared to similar studies (Diels & Howarth, 2011) despite our 10-minute exposure being relatively long (Bonato et al., 2008; Ji et al., 2009). However, these studies utilized either visual yaw rotation or alternating optic flow stimuli, which might explain higher VIMS scores. In fact, Bonato and colleagues (2008) found increased vection scores but reduced VIMS scores during constant optic flow compared to alternating optic flow. These findings also point in the direction that the intensity of vection does not predict VIMS, but rather that there are other factors in the visual scene that are decisive in VIMS. That our stimulus was successful in inciting high vection scores, but was compared to stimuli used by other studies not necessarily provocative substantiates this point. Further research could shed light on identifying those elements of a visual scene that are pivotal in inducing visually induced motion sickness, and those elements that are key in inducing specifically vection. Several potential causes for VIMS are discussed in an overview by Keshavarz and colleagues (2015).

Our findings, similar to several prior vection studies, reinforce the notion that while vection plays a role in VIMS the relationship between them is not straightforward. VIMS remains a multi-faceted phenomenon, and no unifying theory that consistently predicts its occurrence exists. Other factors, such as frame information, might be essential components in understanding VIMS. The possibility that vection is not the decisive nor principal factor underlying VIMS should be considered.

Chapter 5

Moving base driving simulators' potential for carsickness research

Kuiper, O.X., Bos, J.E., Diels, C., & Cammaerts, K. (2019). Moving base driving simulators' potential for carsickness research. *Applied ergonomics*, *81*, 102889.

Abstract

Objective: We investigated whether motion sickness analogous to carsickness can be studied in a moving base simulator, despite the limited motion envelope. Importantly, to avoid simulator sickness, vision outside the simulator cabin was restricted.

Methods: Participants (N = 16) were exposed blindfolded to 15-minute lateral sinusoidal motion at 0.2 Hz and 0.35 Hz on separate days. These conditions were selected to realize optimal provocativeness of the stimulus given the simulator's maximum displacement and knowledge on frequency-acceleration interactions for motion sickness.

Results: Average motion sickness on an 11-point scale was 2.21 ± 1.97 for 0.2 Hz and 1.93 ± 1.94 for 0.35 Hz. The motion sickness increase over time was comparable to that found in studies using actual vehicles.

Conclusion: We argue that motion base simulators can be used to incite motion sickness analogous to carsickness, provided considerable restrictions on vision. Future research on carsickness, potentially more prevalent in autonomous vehicles, could benefit from employing simulators.

5.1. Introduction

Motion sickness is a state of discomfort which can be caused by real or apparent motion (Reason & Brand, 1975). The underlying neural mechanism of motion sickness has been theorized to be a mismatch between actual and anticipated sensory signals, which can be modulated by visual-vestibular conflicts (Oman, 1990; Bles et al., 1998; Bos et al., 2008). Motion sickness can occur in multiple distinct forms including seasickness, carsickness, airsickness, and –more recently– forms involving artificial visuals such as simulator sickness and cybersickness (Golding, 2006b). Regardless of nomenclature, all such forms of motion sickness are understood as resulting from a similar mismatch in sensed and expected motion. However, there are also discernible differences between these forms. For example, seasickness, in addition to by definition occurring at sea, invariably involves a component of actual motion, i.e. external motion perturbation through ship movement (Lawther & Griffin, 1986). Conversely, in the case of cybersickness external motion perturbations are absent but the artificial visuals suggest motion leading to a visual-vestibular conflict, and subsequently to motion sickness (Davis et al., 2014).

Carsickness is motion sickness that results from provocative motion frequencies occurring in a road vehicle in transit, and can be exacerbated by mainly by visual factors (Turner & Griffin, 1999; Perrin et al., 2013; Griffin & Newman, 2004a; Kuiper et al., 2018). The recent literature reports on comparatively few studies concerning carsickness (Kato & Kitazaki, 2006; Wada et al., 2012). Despite this limited interest, studies have indicated that about two-thirds of the population have suffered from carsickness at some point in their lives (Reason & Brand, 1975). Furthermore, autonomous vehicles, which are projected to become widespread in the coming decades, are expected to significant increase the likelihood of carsickness (Diels & Bos, 2016). While the frequency dependency of provocative motion is reasonably well understood (O'Hanlon & McCauley, 1974; Lawther & Griffin, 1987; Bos & Bles, 1998) most data originates from experiments using vertical motion, which is subordinate to horizontal motion in cars (Griffin & Newman, 2004b). In addition, the functional role of visual-vestibular interactions in carsickness is not fully understood. Therefore, additional research into carsickness seems warranted.

Provided it is possible to reproduce specifically those motion cues that lead to carsickness, research into carsickness could benefit from utilizing moving base simulators. As opposed to on-road vehicle experiments, simulators offer a safe research environment and have the methodological advantage in their degree of controllability and replicability of motion and visual cues. Using simulators to investigate carsickness, however, firstly requires a thorough understanding of simulator sickness and secondly the prerequisite that the motion base can provide sufficient provocative motion to induce motion sickness. In the present study, we will discuss these two problems and investigate whether in a principal case a simulator can approximate car motion (i.e. the accelerations) of a sinusoidal motion resembling a slalom, and can induce motion sickness if visual factors are excluded.

Simulator sickness is commonly defined as motion sickness following any use of a simulator that leads to motion sickness (Hettinger et al., 1987; Brooks et al., 2010), and is primarily known as a practical problem causing participant drop-out when using simulators for training purposes (Reed et al., 2007; Mourant & Thattacherry, 2000). Typical simulator sickness can result either from *exclusively* the visual suggestion of motion, or from the *combination* of visual and vestibular cues. In a fixed base simulator, simulator sickness is somewhat akin to cybersickness (Hettinger et al., 1990), however, in a moving base simulator an interaction between visual and motion cues is at issue (Stanney et al., 1997). It should be noted that if a scenario leads to carsickness (e.g. a slalom), that scenario in a simulator also leading to sickness is not necessarily typical simulator sickness. Rather, it could be that the simulator resembles the real situation sufficiently that it the motion sickness is caused by the same sensory conflict. However, due to the inherent difference between a driving simulator and a car in motion, it is very hard to identify the relevant sensory aspects that cause carsickness, and what (combinations of) sensory inputs lead to simulator sickness.

Therefore, to determine whether simulators can in fact be used to investigate carsickness, we would argue it should first be established without involvement of visual factors whether a moving base driving simulator can induce motion sickness. Visual cues are always central in simulator sickness, while for carsickness, mainly vestibular motion cues are at issue, possibly exacerbated by a visual-vestibular conflict (Kamiji et al., 2007). In fact, often precisely the lack of vision out-the-window aggravates carsickness (Griffin & Newman, 2004a; Kuiper et al., 2018). Thus, restricting vision out of the vehicle or simulator cabin during motion is compatible with carsickness, and even a naturally occurring facilitating factor.

In addition, if artificial visuals are present, differentiating what factors exactly cause sickness in a simulator is quite difficult (Kennedy & Fowlkes, 1992). The extent to which the artificial visuals lead to perceived self-motion and subsequent sickness depends on a plethora of factors, such as field-of-view, latency, depth or stereo vision, and contrast (Lin et al., 2002; Diels et al., 2007; Moss & Muth, 2011). While on the one hand, a larger field-of-view has repeatedly been shown to lead to increased sensation of self-motion (Allison et al., 1999; Van Emmerik et al., 2011; Grácio et al., 2014), visual information that is excessively incongruent with expectations can potentially even be disregarded for self-motion perception, a phenomenon called 'quarantining' (Golding et al., 2009). For these reasons, restricting vision outside the simulator cabin prevents simulator sickness' predominant visual component, and might allow study of sensory conflict as it would occur based on motion accelerations as they occur in a vehicle with no outside vision.

An additional issue with the use of driving simulators to investigate carsickness is their limited motion envelope, i.e., their limitations with respect to position, velocity and acceleration. Moving base simulators using a Stewart platform, for instance, are limited in their displacements, while xy-platforms offer a far greater range of motion. With respect to motion sickness, the frequency capabilities of the motion platform is of particular interest because motion in the frequency range around 0.2 Hz has been extensively shown to be most provocative for vertical (O'Hanlon & McCauley, 1974; ISO2631-1, 1997). There is also evidence this is the case for horizontal motion (Golding et al., 2001). When using a motion base simulator to study motion sickness, to maximize provocativeness its frequency and acceleration capabilities should be carefully considered, as limited motion might not lead to any sickness to study (Golding, 2006b).

Somewhat counterintuitively, selecting a frequency of 0.2 Hz does not necessarily lead to the most provocative stimulus, if displacement is a limiting factor. Assuming a motion platform where the side-to-side displacement is the main limiting factor, that maximum displacement is a given parameter for a sinusoidal motion when maximizing provocativeness. Subsequently, the selected frequency is then directly related in magnitude to peak acceleration by the nature of a sinusoidal wave function. Following ISO 2631-1(1997), Figure 5.1 shows that if freely selecting a frequency and maximum acceleration, the peak of sickness incidence is at about 0.2 Hz (left panel). Note that here displacement differs with frequency. However, if displacement is set, and thus frequency influences maximum acceleration, a frequency of 0.35 Hz maximizes expected sickness (right panel). This corresponds to a factor of 1.57 higher for 0.35 Hz compared to 0.2 Hz with the same amplitude. Thus, in order to maximize provocativeness for a set amplitude, a frequency of 0.35 Hz is expected to be ideal based on the ISO 2631-1.

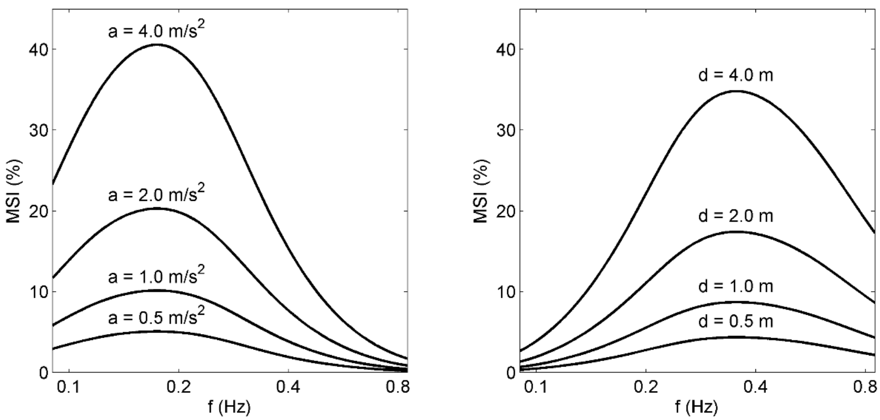

Figure 5.1. Calculations based on ISO 2631-1(1997) showing the percentage of motion sickness incidence (MSI) depending on frequency sinusoidal motion lasting for 15 minutes. Left: calculations using fixed RMS accelerations (a). Right: calculations using fixed peak-to-peak displacements (d).

In the present study we aimed to establish whether motion sickness analogous to carsickness can be induced using a simulator. To prevent simulator sickness, we exclusively use the simulator motion base, and excluded all visual cues by blindfolding participants. In addition, we aimed to establish what parameters for a sinusoidal motion would maximize motion sickness given the limited amplitude of the simulator. We compared two 15-minute conditions. at 0.2 Hz and at 0.35 Hz and measured motion sickness with a self-reported scale every minute during the experiment.

5.2. Methods

5.2.1. *Participants*

Sixteen healthy adults voluntarily participated, 14 males and 2 females with a mean age of 37.31 years (SD = 13.5 years). All participants signed an informed consent form in advance, and indicated they were free of ocular and vestibular disorders and had normal or corrected-to-normal vision. All experimental procedures were conducted in accordance with the ethical guidelines of the Declaration of Helsinki.

5.2.2. *Apparatus*

The simulator was a moving base driving simulator consisting of a lateral sled on which a 6DoF motion platform was mounted with a car cabin. See Figure 5.2 The maximum lateral displacement of the x-y platform was 100cm from the center, i.e., 2 m peak-to-peak. However, the maximum displacement utilized in this experiment was 120cm peak-to-peak to ensure a sinusoidal motion at the selected frequencies could be presented smoothly. The maximum lateral acceleration of the simulator was 7.4 m/s^2. We did not make use of the simulator's additional motion capabilities in this experiment, thus all motion to which participants were exposed was lateral displacement on a single axis of motion. In terms of available lateral displacement, the simulator in the present study falls between two most common types of motion base simulators: those with only a Stewart platform (typically 20-100 cm peak-to-peak lateral displacement) and those with a linear track system in combination with a hexapod (up to many meters of lateral displacement).

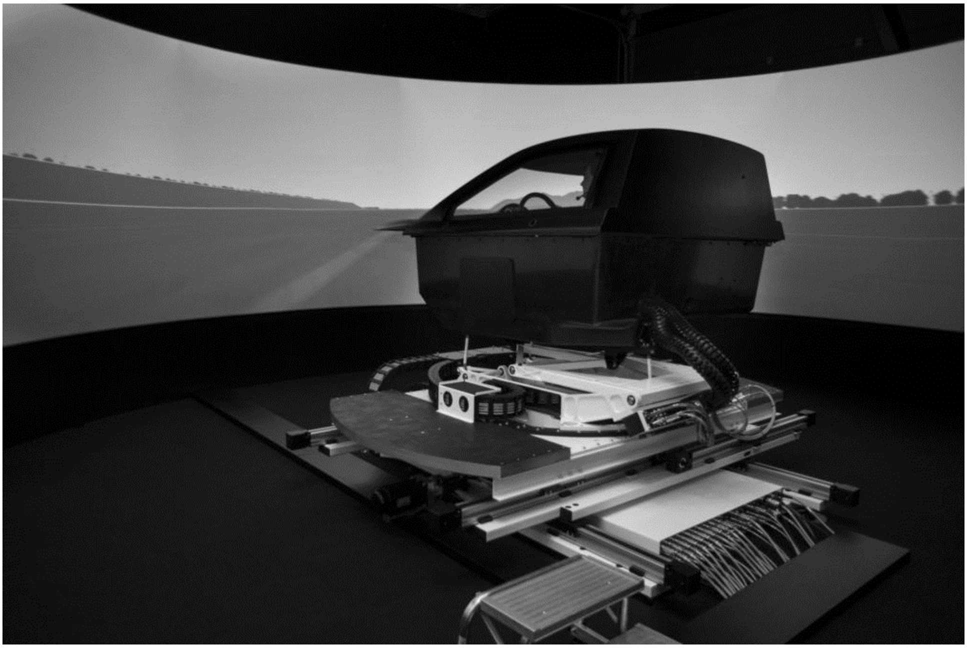

Figure 5.2. The motion simulator. The partial vehicle cabin is lightweight and allows the x-y platform to smoothly move. For the present study we exclusively used lateral motion. Note that the visuals during the experiment were turned off, and the participant was blindfolded.

5.2.3. *Experimental conditions and stimulus*

Two conditions were realized at two different frequencies in otherwise identical circumstances. These two conditions were 1) the 0.2 Hz condition, corresponding to a peak acceleration of 0.95 m/s^2, and 2) the 0.35 Hz condition, corresponding to a peak acceleration of 2.90 m/s^2. Each condition lasted for 15 minutes and lateral sinusoidal motion had an amplitude of 60 cm, i.e. 120cm peak-to-peak. The stimulus was comparable in the relevant low frequency motion to slalom driving (Kuiper et al., 2018) or a continuous series of lane changes (Bellem et al., 2017).

5.2.4. *Ratings*

Prior to the first condition, participants filled out the motion sickness susceptibility questionnaire (MSSQ), adapted from Golding (2006a). The MSSQ gives an indication of a participant's susceptibility to motion sickness based on their past experiences. This was done to ensure that our population of participants was representative for the general population in terms of motion sickness susceptibility.

Our primary dependent variable was the MISC rating, an 11-point rating scale for motion sickness (MISC, also known as the misery scale, see Table 5.1, taken from Bos et al., 2005). This scale utilizes the fact that motion sickness is characterized by a multiple of symptoms such as sweating and dizziness, followed by nausea, retching and ultimately vomiting. Once the participant is familiar with this scale, employing it only takes a few seconds, i.e. the participant reports a single number when prompted. This allows for the scale to be easily applied repeatedly throughout the experiment.

Table 5.1. 11-point MIsery SCale (MISC) (Bos et al., 2005)

Symptoms		Misc
No problems		0
Some discomfort, but no specific symptoms		1
Dizziness, cold/warm, headache, stomach/throat awareness,	Vague	2
sweating, blurred vision, yawning, burping, tiredness,	Little	3
salivation, . . . but no nausea	Rather	4
	Severe	5
Nausea	slight	6
	fairly	7
	severe	8
	(near) retching	9
Vomiting		10

5.2.5. *Procedure*

Conditions were counterbalanced across participants to compensate for order effects. After briefing, signing of informed consent, filling out the MSSQ, and explaining the MISC, participants took place in the front seat of the simulator cabin. Participants were seated upright, were blindfolded, and were presented with white noise over headphones. In this way only vestibular and proprioceptive cues differed between conditions. During the experiment, participants were prompted to report their level of motion sickness on the MISC scale (Bos et al., 2005) at one-minute intervals. Simulator motion was stopped when any level of nausea (i.e., MISC > 5) was reported, or after 15 minutes had passed, whichever came first. Having at least 24 hours before the start of the next condition allowed participants to recover from any sickness in the previous condition, to further minimize any cross-over effects.

5.3. Results

The average MSSQ total score of participants was 11.20 ± 10.16. This corresponds with a slightly below average susceptibility (Golding, 2006a). The 14 men had MSSQ scores of 12.67 ± 10.24 , while for the two females scores were relatively low (4 and 0.8). This is atypical as generally women are somewhat more susceptible (Dobie et al., 2001; Chapter 2). MSSQ scores and motion sickness scores after 15 minutes were not significantly correlated for the two conditions (r = 0.046, p = .877 and r = 0.003, p =.991 for 0.2 Hz and 0.35 Hz respectively).

Motion sickness increased over the 15-minute time period for both conditions. The average illness rating after 15 minutes was 2.21 ± 1.97 in the 0.2 Hz condition, and 1.93 ± 1.94 in the 0.35 Hz condition. Figure 5.3 shows the illness ratings of participants for the two conditions over the entire 15-minute period. A repeated measures ANOVA revealed a significant increase in illness score over time for both conditions ($F(1,195) = 11.872$, $p < .001$, partial $\eta^2 = 0.477$). However, there was no significant effect of the two conditions on illness scores ($F(1,195) = 0.249$, $p = .626$, partial $\eta^2 = 0.019$). In fact, there was a strong correlation between participants' MISC scores at t=15 for the two conditions ($r = 0.770$, $p < .001$).

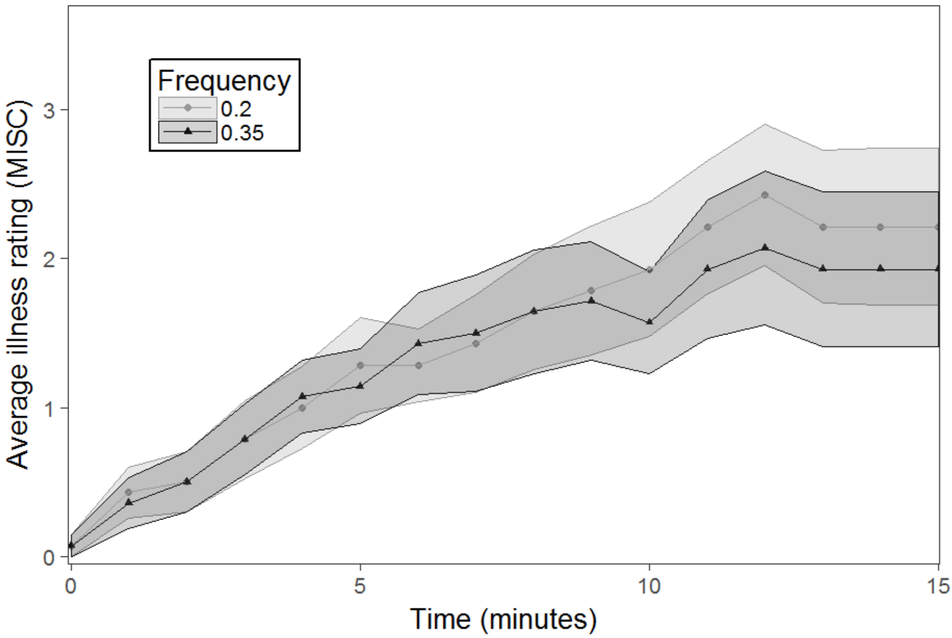

Figure 5.3. Average illness ratings over time for the 0.2 Hz and the 0.35 Hz condition. Grey areas depict SEM.

Regarding the percentages of participants over time that reached certain thresholds of illness rating (MISC) is another way to explore the data. In most motion sickness studies, generally a portion of participants show no effect to the provocative stimulus (see e.g. Dong et al., 2011; Perrin et al., 2013). After 5 minutes, 75% of participants in our study reported initial motion sickness effects. During the entire 15-minute exposure, 20% of participants did not report any illness symptoms in either condition (i.e. a score of 2 or more). Both of these trends can be seen in Figure 5.4.

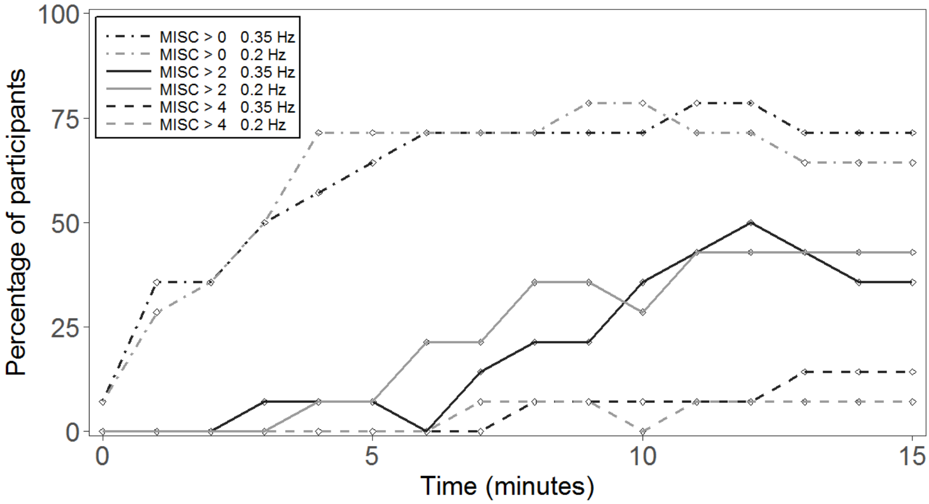

Figure 5.4. Percentage of participants over time that reach a certain illness score or higher (MISC).

5.4. Discussion

In the present study we studied whether motion sickness, analogous to carsickness, here realized via a vestibular-proprioceptive conflict, can be induced using a moving base driving simulator. We blindfolded participants to ensure that no visual confounding factors were in play. We were successful in inducing motion sickness in three-quarter of participants. Both the fraction of participants reporting illness over the duration of the experiment and the overall severity of motion sickness were comparable to studies employing actual vehicles. These studies utilized, notably, similar provocative lateral accelerations, i.e. slalom of similar or larger amplitude (Kuiper et al., 2018; Wada & Yoshida, 2016). The percentage of participants in a 15-minute timeframe reporting initial motion sickness symptoms in our study even exceeds that of a study using exposure to normal non-slalom drives for 30 minutes (Griffin & Newman, 2004a). Ratings we found were thus at least comparable in severity to on-road studies; our large fraction of male participants and lack of visual-vestibular conflict might have even led to potentially lower scores (Cheung, & Hofer, 2002; Perrin et al., 2013; Kuiper et al., 2018). We therefore argue that a motion base driving simulator can in principle induce motion sickness analogous to carsickness, i.e. resulting primarily from low frequency motion.

While the velocity of a vehicle plays a large role in the driving experience, velocity has no direct bearing on our vestibular organs, pivotal in motion sickness. These organs are only sensitive to accelerations, i.e. changes in velocity (Mayne, 1975; Reason & Brand, 1975). In our experiment, the sensory input that leads to sickness was no different to the sensory input that principally leads to carsickness: low-frequency motion. This range of motion frequencies are, in a road vehicle, generally the result of acceleration and deceleration, cornering, and lane changes (Griffin & Newman, 2004b). Using the right motion platform, the relevant frequency component of these motions cannot just be *simulated* but *recreated* in a simulator, thus potentially allowing researchers to apply exactly those motions which are principal to carsickness.

Assuming the same lateral displacement, we expected to find higher motion sickness scores at 0.35 Hz compared to 0.2 Hz, by a factor of 1.57 based the ISO2631-1. Although not statically significant, we observed a trend in the opposite direction. A possible explanation for these findings it that, while often generalized for horizontal motion, the ISO is based on vertical motion data. There is evidence that the frequency weighting for lateral motion, while also peaking at 0.2 Hz, is possibly distributed differently (Golding et al. 2001; Griffin & Mills, 2002; Donohew & Griffin, 2004). Motion frequency might play a larger role than peak acceleration in lateral motion as compared to vertical motion. An alternative explanation for the lack of difference between conditions is that in the 0.35 Hz condition the higher acceleration could have provided additional somatosensory cues via touch of the racing seat, or via vibration artefacts of the simulator, reducing illness. Overall, there is limited data available in the literature on the effect of motion frequency and acceleration for lateral motion, and our sample size was not sufficient to draw conclusions. More research on the relation between lateral motion and motion sickness is necessary, as lateral motion is the principal component of carsickness (Griffin & Newman, 2004a).

An advantage of researching motion sickness analogous to carsickness in a simulator is that it enables a wide variety of research that is potentially unsafe if preformed in a normal car, such as transfer of control in autonomous vehicles. Initially, such vehicles are expected to facilitate automated driving on select roads, with a moment of transfer of control back to the passenger when entering an area where automated driving is not supported (SAE, 2014). However, as passengers engage in non-driving activities during automated driving, their outside view is generally restricted, which exacerbates carsickness (Griffin & Newman, 2004a). Motion sickness has been found to degrade task performance (Rolnick & Bles, 1989; Bos, 2004), possibly degrading driving skills and thus creating unsafe situations if occupants are carsick. A second topic of research that could benefit from recreating carsickness in a simulator is that of countermeasures against motion sickness, i.e. providing addition sensory information to reduce sensory conflict and increase the ability to anticipate the motion (Rolnick & Lubow, 1991). Such measures have already been shown to be effective in both flight and ship simulators (Feenstra et al., 2011; Tal et al., 2012), but have only very limitedly been investigated in cars (Miksch et al., 2016; Kuiper et al., 2018; Salter et al., 2019). In addition to visual information, there is evidence that auditory (Keshavarz & Hecht, 2014) or olfactory cues (Keshavarz et al., 2015), both easily implementable in a car interior or simulator cabin, can influence motion sickness.

Compared to blindfolded, vision on the cabin interior, such as when using a display for work or entertainment as one might do in an automated vehicle, could potentially increase the occurrence of sickness. This is due to increased visual-vestibular discrepancy as a result of the static visual scene (Probst et al., 1982; Bos et al., 2005; Griffin & Newman, 2004; Kuiper et al., 2018). Research on the effect of reading or display-use during exposure to provocative accelerations is easily realizable in a simulator, and could test the effect of occupant behavior during automated driving at a moment when vision out of the simulator cabin is not relevant, thus avoiding the visual component of simulator sickness. Furthermore, these research paradigms can easily be expanded by including factors such as head position (Wada & Yoshida, 2016) or distraction (Bos, 2015). It should be noted that for carsickness, view on the car interior is more detrimental than having eyes closed, while vision out of the window is most beneficial (Probst et al., 1982; Griffin & Newman, 2004; Wada & Yoshida, 2016).

Concluding, our findings suggest that moving base driving simulators have potential for studying motion sickness analogous to carsickness. We found motion sickness scores to increase over time at a similar rate as compared to on-road studies using similar motion stimuli. By restricting participants' vision, we excluded the visual conflicts associated with simulator sickness. It must be noted that researchers attempting to study carsickness should be vigilant that illness in a simulator is the result of a sensory conflict similar to carsickness, rather than of simulator sickness. In addition, the motion platform needs to be capable to generate accelerations equivalent to the relevant car accelerations. Within the constraints we mention, we believe simulators have potential to be used for carsickness research.

Chapter 6

Knowing what's coming: unpredictable motion causes more motion sickness

Kuiper, O.X, Bos, J.E., Schmidt, E.A., Diels, C., Wolter, S. (Accepted in *Human Factors*) Knowing What's Coming: Unpredictable Motion Causes More Motion Sickness. DOI: 10.1177/0018720819876139

Abstract

Objective: Anticipation is thought to play a role in motion sickness by reducing the discrepancy between sensed and expected sensory information. However, both the exact role and potential magnitude of anticipation on motion sickness are unknown. This study explores the role of anticipation in motion sickness. We compared three conditions varying in motion predictability and assessed the effect of anticipation on subsequent illness ratings using a within-subjects design.

Methods: Participants (*N* = 17) were exposed to three 15-minute conditions consisting of repeated fore-aft motion in an enclosed cabin on a sled on a 40 m rail. 1) at constant intervals and consistent motion direction 2) at constant intervals but varied motion direction, and 3) at varied intervals but consistent motion direction. Conditions were otherwise identical in motion intensity and displacement, as they were composed of the same repetitions of identical blocks of motion. Illness ratings were recorded at 1-minute intervals using a 11-point motion sickness scale.

Results: Average illness ratings after exposure were significantly lower for the predictable condition, compared to both the directionally unpredictable condition and the temporally unpredictable condition.

Conclusion: Unpredictable motion is significantly more provocative compared to predictable motion. Findings suggest motion sickness results from a discrepancy between sensed and expected motion, anticipation being an important factor herein. This study underlines the importance of an individual's cognitive state in motion sickness. Furthermore, this knowledge could be used in domains such as that of autonomous vehicles to reduce carsickness.

6.1. Introduction

Motion sickness is an unpleasant state of discomfort resulting from exposure to motion. It is characterized by a feeling of malaise and symptoms such as sweating, pallor, dizziness, nausea, and eventually vomiting. Experienced by a large portion of the population at some point in their life as carsickness or seasickness (Reason & Brand, 1975), motion sickness is an undesirable side-effect affecting multiple modes of transport and could become an even more substantial problem in autonomous vehicles due to more people travelling as passengers possibly engaging in visual non-driving activities (Diels & Bos, 2016).

A multitude of factors influence how motion sickness develops as a result of motion. For instance, motion frequency is well established to influence motions sickness, with frequencies around 0.2 Hz being the most provocative (O'Hanlon & McCauley, 1974; Donohew & Griffin, 2004; Golding et al., 2001). Visual information, or lack thereof such as when reading in a vehicle, can exacerbate motion sickness and has been studied extensively (Probst et al., 1982; Griffin & Newman, 2004; Perrin et al., 2013; Kuiper et al., 2018). There also exists evidence that an individual's anticipation of the motion influences the extent to which motion sickness develops (Rolnick & Luwbow, 1991; Feenstra et al., 2011). In this study we focus on the latter, the effect of anticipation of motion on subsequent motion sickness.

Relatively few studies dedicated to the subject of anticipation and motion sickness exist in the literature. Rolnick and Luwbow (1991) found that when exposed to identical motion on the same motion platform, the participant in control of the motion became less motion sick. This effect was attributed to the participant in control having increased anticipation of the motion. Feenstra and colleagues (2011) found that in in a 6-dof flight simulator motion sickness was significantly reduced by providing the participant with visual information about upcoming motion. These studies had the drawbacks of either being between subjects (Rolnick & Lubow, 1991), or of being coupled with another intervention (Feenstra et al., 2011), offering only limited information on the precise role and effect size of anticipation on motion sickness. However, in addition to these studies, the idea that anticipation could play a role in motion sickness is mentioned frequently in the literature. It might potentially explain in part the benefits of vision in carsickness (Perrin et al., 2013; Bos et al., 2008; Kuiper et al., 2018). However, the exact importance of anticipation in this matter is currently unknown and therefore worthwhile of further investigation.

Interestingly, the root cause of motion sickness has been theorized to be related to anticipation, namely to be a discrepancy between sensed and expected sensory information (Reason & Brand, 1975; Reason, 1978; Oman, 1990; Bos & Bles, 2002; Bos et al., 2008). That is, external perturbations introduce uncertainty in the sensory feedback expected as a result of self-initiated changes in body state (which are estimated using an internal model containing an 'efference copy'); the magnitude of that error between sensed and expected is linked to motions sickness. In this article, we will not further explore the model, but rather focus on the effects of anticipation on motion sickness in an experiment study.

Therefore, in the present study we designed a within-participants experiment to investigate the effect of anticipation of motion on subsequent motion sickness. To isolate the effect of anticipation, it was essential to use conditions that were highly identical in terms of motion frequency and intensity. To that end we used a simple for-and-backward motion that was presented repeatedly 1) at fixed intervals and always in the same direction, 2) at fixed intervals but in a varying direction, and 3) at variable intervals but always in the same direction. Our hypothesis is that conditions that offer motion stimuli that are unpredictable either in direction or in timing will lead to more sickness compared to a condition of motion that is completely consistent and thus allows for anticipation.

6.2. Methods

6.2.1 Participants

Approval by the TNO Human Factors institutional Review Board on Experiments with Human Subjects was obtained in accordance with the ethical standards laid down in the 2013 Declaration of Helsinki. All participants indicated they were free of vestibular disorders and in otherwise good health, and had not been drinking alcoholic beverages during 24 h in advance of the experiment. Prior to the first experimental condition the experiment was explained and participants signed an informed consent form. A total of 17 participants, 5 males and 12 females, took part in the experiment, ranging in age from 21 to 52 years with an average age of 39.64 (*SD* = 10.9).

6.2.2 Apparatus

The motion profiles were realized using a cabin moving on a 40m track by means of 48 wheels (oriented in rows on three sides of each rail – similar to common rollercoaster design). The cabin was moved by being pulled forward- or backward by two synthetic (high molecular weight polyethylene) cables, driven by two motors positioned on each far side of the track. See Figures 6.1 and 6.2 for the track and cabin. The cabin prevented visual and air-flow cues that give information on the occurrence and direction of motion. Inside the cabin a rally car seat was fixed to the base of platform, offering a headrest and a 5-point safety belt.

Figure 6.1. The motion platform and track. The full track was 40 m, however, in the present study we exclusively utilized displacements of 9 m. Figure 6.2: The inside of the cabin with the car seat and 5-point safety harness. The cabin prevented visual and haptic (via airflow) information on the occurring motion.

6.2.3 Motion profile and conditions

The three conditions were all based on repetition of a single displacement of for- and backward raised cosine motion that was repeated for 15 minutes. The conditions differed by presenting the displacements: 1) at fixed intervals and in a fixed direction (predictable, P), 2) at fixed intervals but in a variable direction (directionally unpredictable, dU), and 3) at variable intervals while keeping the direction fixed (temporally unpredictable, tU). See Figure 6.3.

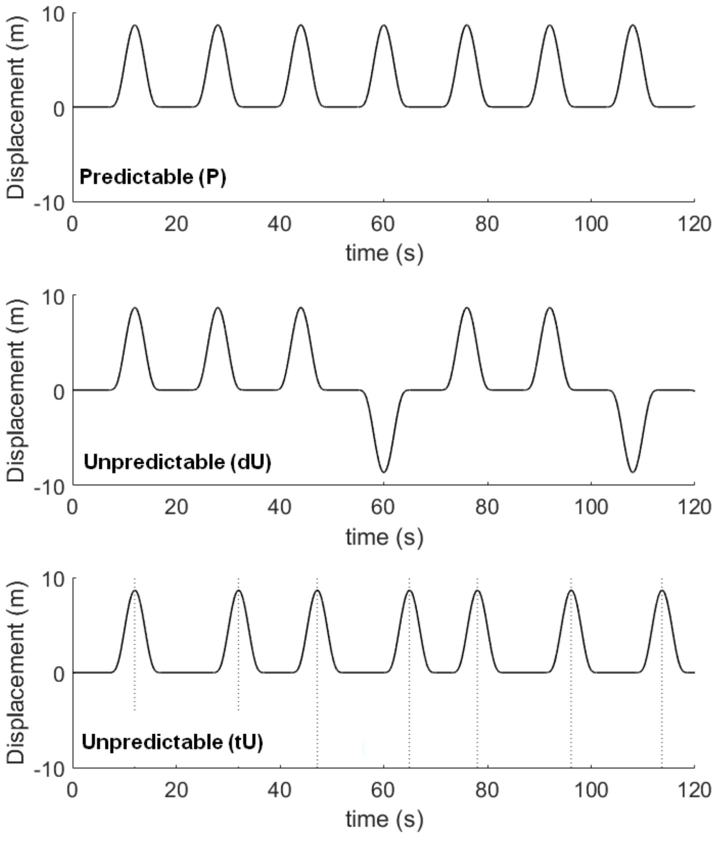

Figure 6.3. An example of the first two minutes of the three conditions, showing displacement over time. Over the 15-minute duration, all conditions use the same amount of repetitions of the basic displacement. From top to bottom

the conditions shown here are predictable (P), directionally unpredictable (dU), and temporally unpredictable (tU).

Each single displacement lasted for 8 seconds and had an amplitude of 9.0 meters, corresponding to a peak acceleration of 2.49 m/s^2. On-and offset were slightly adapted to have a smooth transition to stationary rather than a sudden change in acceleration. In condition P and dU, there was a fixed 8 second pause between each displacement, resulting in a regular 16 seconds cyclic motion. In condition dU, half of the displacements had their sign inverted semi-randomly, i.e. motion was backward-then-forward instead of forward-then-backward. In condition tU, the pauses in between the displacements were varied semi-randomly between 4 and 12 seconds, still averaging 8 s over the 15-minute experiment.

The root mean square (RMS) of acceleration was identical in all three conditions. Acceleration RMS is a main factor in predicting motion sickness (O'Hanlon & McCauley, 1974; Lawther & Griffin, 1986; ISO 2631, 1997). The motion profiles of the three conditions were calculated using the ISO 2631 to lead to highly similar motion sickness vomiting incidences, which corresponds with a MISC of 10, of respectively 7.43, 7.52, and 7.43 for the P, uD, and uT conditions. Do note, however, that the ISO does not take into account predictability of the stimulus to calculate expected motion sickness incidence, only the physical motion over time.

6.2.4 MISC

To assess the participants' motion sickness, the 11-point *Misery Scale* (MISC) was used (Table 6.1, Bos et al., 2005). Both before the experiment and at 1-minute intervals during the 15-minutes, the participant indicated their score on the MISC. The scale is based on the knowledge that nausea, retching and vomiting as a result of motion sickness are virtually always preceded by initial symptoms such as sweating, yawning, apathy, stomach awareness, and dizziness. These latter symptoms may vary between participants but are generally found to monotonically rise in severity if motion is not halted. A MISC of 6 or higher (i.e., any nausea), was taken as a cut-off point to end a condition. In the case of stopping a condition mid-way due to nausea, the last reported MISC score was, conservatively, assumed to remain the same for the subsequent time points.

Table 6.1.
11-point MIsery SCale (MISC) (Bos et al., 2005)

Symptoms		MISC
No problems		0
Some discomfort, but no specific symptoms		1
Dizziness, cold/warm, headache, stomach/throat awareness,	vague	2
sweating, blurred vision, yawning, burping, tiredness,	little	3
salivation, . . . but no nausea	rather	4
	severe	5
Nausea	slight	6
	fairly	7
	severe	8
	(near) retching	9
Vomiting		10

6.2.5 Procedure

To get insight into the susceptibility of our subjects relative to a normal population, prior to the first condition participants filled out the motion sickness susceptibility questionnaire (MSSQ; Golding, 2006). Following this, the MISC and experimental procedural were explained. Participants were instructed to keep their eyes open during the experiment and their head in a static but comfortable position. Whenever participants felt nauseated, they were instructed to indicate this. Each condition took place on a separate day for a participant, to allow for full recovery from any residual motion sickness. Conditions were counterbalanced to prevent order effects.

Participants were informed that one condition was highly repetitive in terms of motion, while the other two either differed in the direction or in timing between displacements. We did not explicitly encourage participants to be cognizant of their ability to anticipate motion. The experimenter was in contact with the participant via a two-way auditory connection over headset and could see the participant by means of a one-way video connection. During the experiment, white noise was played via a headset to mask the sound of the motors.

6.3. Results

MSSQ scores of participants were on average 9.80 (SD = 5.36). This falls between the 50th and 60th percentile in terms of motion sickness susceptibility of a normal population (Golding, 2006).

After 15-minutes the average illness ratings were: 2.36 (SD = 1.95) for the predictable condition (P), 3.58 (SD = 1.59) for the directionally unpredictable condition (dU), and 3.58 (SD = 1.65) for the temporally unpredictable (tU) condition. See Figure 6.4 for participants' illness ratings for the three conditions over the entire 15-min period.

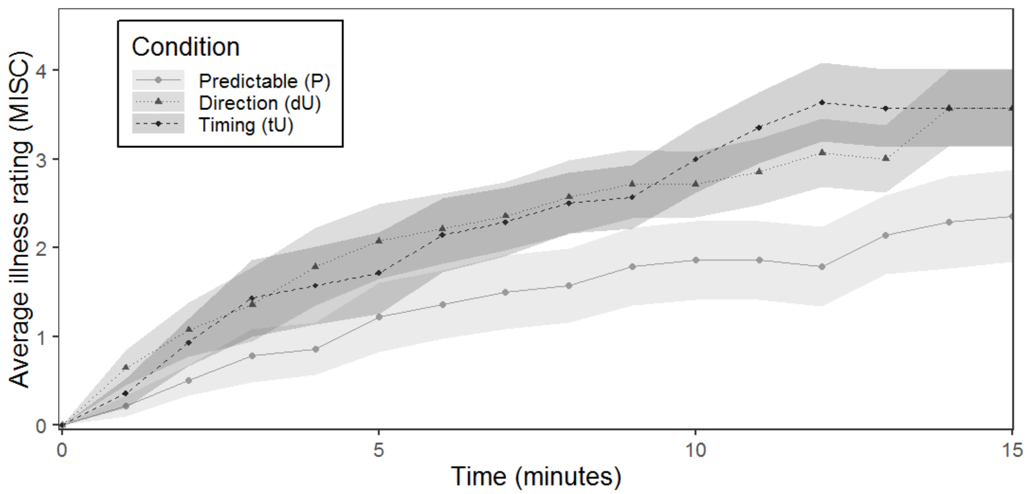

Figure 6.4. Average illness ratings over time for the predictable (P), the directionally unpredictable condition (dU), and the temporally unpredictable (tU) conditions. Grey bands depict SEM.

A repeated measures ANOVA showed a significant effect of time on motion sickness (F(15,195) = 12.68, p < .001, partial η2 = 0.747), and of condition on motion sickness (F(2, 26) = 14.35, p < .001, partial η2 = 0.481). A non-parametric Friedman test on the scores at 15 minutes again showed a significant difference between the three conditions ($\chi^2(2)= 10.33$, $p = .006$). Subsequent Wilcoxon signed ranked tests showed that both unpredictable conditions differed from the predictable condition ($Z = -2.53$, $p = .012$ for dU and P, and $Z = -2.66$, $p = .008$ for dU and P), while the unpredictable conditions did not differ ($Z = 0.00$, $p > 0.5$).

To investigate the increase of sickness over time, we fitted regression lines to the MISC data, one for each condition, using a square root function. A square root function was a better fit when compared to a linear model, yet had the advantage of containing only one parameter preventing overfitting. See Figure 6.5 for the regression lines. These regression lines also significantly differed for P versus dU ($F(1,444) = 5.0319$, $p = .025$) and for P versus tU ($F(1,444) = 10.783$, $p = .001$), but not for dU versus tU ($p = .276$). These statistics were calculated using a dummy variable for the conditions and examining the interaction effects of the models.

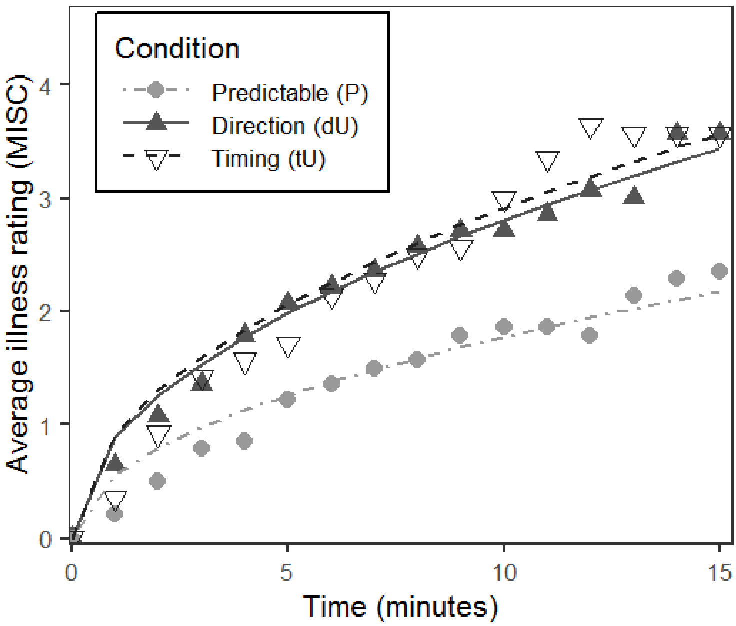

Figure 6.5. Regression line per condition using a square root function.

Finally, we calculated regression lines for each participant and for each of the three conditions, again using a square root function. This approach had the advantage of showing interpersonal differences in the slope of increase of motion sickness over time. See Figure 6.6. A non-parametric Friedman test on the coefficients per condition showed a difference between the three ($\chi^2(2) = 9.57$, $p = .008$). Subsequent Wilcoxon signed ranked tests indicated that both unpredictable conditions differed from the predictable condition ($Z = -2.63$, $p = .009$ comparing dU to P, and $Z = -3.56$, $p < .001$ comparing tD to P), while the unpredictable conditions did not significantly differ from each other ($Z = -0.43$, $p = .670$).

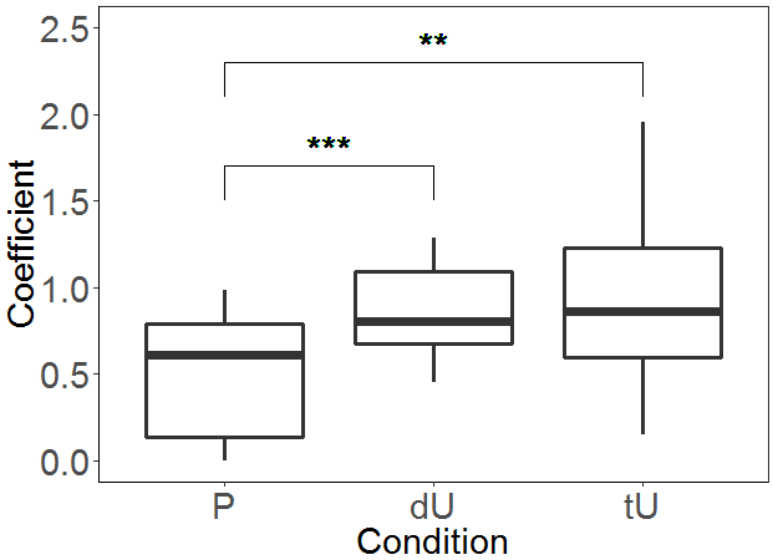

Figure 6.6. Boxplots showing the coefficients of the regression lines fitted for each condition and each participant. Asterisks indicate significance level (** = $p < .01$, *** = $p < .001$). Motion sickness increases at a higher rate for the unpredictable conditions as compared to the predictable condition.

6.4. Discussion

In this study we compared motion sickness scores of participants in three 15-minute conditions consisting of: predictable motion (P), directionally unpredictable motion (dU), and temporally unpredictable (tU) motion. These three conditions consisted of motion identical in terms of displacement and were equally provocative according to ISO calculations – which do not take into account anticipation. In both unpredictable conditions participants reported significantly higher illness scores compared to the predictable condition. This confirmed our hypothesis that unpredictable motion is more provocative than predictable motion.

The differences in scores we found corresponded with 52% higher illness ratings after 15 minutes for the two unpredictable conditions compared to the predictable condition P. This difference between conditions also exists when considering the regression lines, indicating that illness ratings increase at a higher rate in the unpredictable conditions. Our finding, that less predictable motion is more provocative, is in line with other studies that exist in the literature (Rolnick & Lubow, 1991; Feenstra et al., 2011). The study by Rolnick and Lubow (1991) found a comparable (35%) difference between participants that were in control of a motion (and thus could anticipate it), and those that were passively moved in an identical fashion. A study by Feenstra and colleagues (2011) found that illness ratings were reduced by a factor of two in a condition that provided participants with additional visual information on the upcoming motion. This greater difference in scores might be the result of both conditions containing a highly erratic pattern of motion, thus having a high level of unpredictability and a potentially larger effect of the treatment condition. Conversely, since in our study each single displacement was identical, even our unpredictable conditions still had a large degree of predictability in them. However, our design did allow us to isolate unpredictability specifically in timing and directionality. Nevertheless it should be noted that a more erratic pattern of similarly intense motion could potentially be considerably more provocative.

Guignard & McCauley (1982) observed that certain combinations of sinusoidal vertical motion lead to more motion sickness as would be expected by adding the individual effects of single sinusoidal motions. This might be explained by the fact that a simple sinusoidal pattern is repetitive, and therefore more easily allows for anticipations of motion. On the other hand, a more complex combination of sine waves appears erratic to an induvial and its motion could not be anticipated by participants. Interestingly, while these authors recognize that linear addition of provocative motions does not give the full picture, they do not mention any probable causes, including anticipation.

To indicate that our three motion conditions were similar in the relevant physical regards, we calculated their expected provocativeness using the ISO standard, as also used in other studies (Turner & Griffin, 1999; Griffin & Newman, 2004). While this Standard builds on several well-established studies on the effect of motion frequency and intensity on motion sickness, it does not take into account cognitive factors such as anticipation. The ISO standard uses the square root of the integral of the squared frequency weighted accelerations over time; i.e. it considers the acceleration intensity of a motion and uses a frequency weighting centered around 0.167 Hz. However, a clear shortcoming of this standard is that it does not take into account the perspective of the individual, i.e. cognitive factors such as vision and anticipation of motion. We believe our findings underline this shortcoming.

We did not find a difference between unpredictable direction (dU) and unpredictable timing (tU) in terms of motion sickness scores. What this could indicate is that the beneficiary effect of anticipation is not just a state of readiness based on timing, since that would have reflected in scores in the dU condition being equal to the predictable condition. Thus, a likely explanation is that for motion to be properly anticipated, information both on timing and on directionality should be present. This is in line with the theory that the root cause of motion sickness is a discrepancy between sensed and expected motion (Reason and Brand, 1975; Bles et al., 1998). However, the current data does not give a clear insight on the underlying processes, therefore this subject would need to be further explored.

In the literature, visual effects modulating motion sickness are often described in terms of operating through a reduction in visual-vestibular conflict (Probst et al., 1982; Turner & Griffin, 1999; Kuiper et al., 2018). However, this might not be the full picture. In addition to reducing visual-vestibular discrepancy, vision on the external world during motion (e.g. as a car passenger), can improve anticipation of upcoming motion and might therefore be even more beneficial to in reducing motion sickness than generally acknowledged.

Head tilt during motion has been shown to influence carsickness (Wada et al., 2012), therefore it could have been prudent to fixate participants' heads in our experiment. In the dU condition, the directional inversion of the displacements might have led to different head tilt compared to the other two conditions (despite the instructing participants to keep their head in a static position). However, the advantage of not having fixated the head was that this resulted in a more naturalistic situation, i.e. head movement as unrestrained as would occur in a car. For the same reason, we opted to have participants have keep their eyes open, analogous to working in a car with no outside view. Another factor that might have some unforeseen influence occurred in the uT condition. Due to the random timing of this condition, it is possible that per chance some participants experienced an uneven distribution of displacements over the 15-minutes, e.g. as a result of a series of the shortest intervals in a row. While over the 15-minute period this would be compensated with longer intervals (since the average interval was always 8s), such an uneven exposure might have the unintended effect of influencing how motion sickness build up in participants. Note, however, that e.g. the ISO 2631-1 only assumes linear cumulative increase and would not expect increased illness due to this.

Further research on this subject could investigate how to make motion in existing modes of transport more predictable by means of external cues. For example, such information could be beneficial for a passenger of an autonomous vehicle engaged in a screen and thus lacking vision outside. Auditory or haptic information on an upcoming turn or braking maneuver could facilitate anticipation and decrease carsickness. On the other hand, rearward-facing seating in (autonomous) vehicles, as is often shown in concept cars, could limit the occupants' ability to anticipate motion and exacerbate carsickness (Griffin & Newman, 2004; Spencer et al., 2019). Furthermore, if anticipation can also result from recognizing a motion will repeat, as we found in the present study, simply ensuring high consistency in driving behavior (e.g. highly consistent cornering speed and profile in city drives) might decrease carsickness occurrence. In general, researchers could focus on a multitude of modulating factors regarding motions sickness associated with perception of the individual rather than focusing solely on the physical motion characteristics.

The findings presented in this article underline the importance of anticipation in motion sickness. Motion that is more unpredictable, and thus harder to anticipate, is found to be significantly more provocative. While the intensity and frequency of a motion are the fundamental physical aspects that underlie motion sickness, the individual's perception and cognition should not be forgotten by researchers. Not only the intensity of the ride, but also what you see or don't see coming, determine whether it will be a sickening trip or a smooth ride.

Chapter 7

Knowing what's coming: anticipatory audio cues can mitigate motion sickness

Kuiper, O.X., Bos J.E., Diels, C., & Schmidt, E.A. (Under Revision) Knowing what's coming: anticipatory audio cues can mitigate motion sickness.

Abstract

Objective: Being able to anticipate motion is suggested play an important role in mitigating motion sickness as a result of motion, by reducing the discrepancy between sensed and expected sensory information. It is not currently known whether information presented auditory can aid individuals to anticipate motion in a manner that reduces motion sickness. We therefore investigated, in a controlled experiment comparing two conditions, whether such cues could provide a beneficial effect to well-being during provocative erratic motion.

Methods: Participants (*N* = 20) were exposed to two 15-minute conditions consisting of repeated fore-aft motions in an enclosed cabin on a sled on a 40 m rail. The motion events were a semi-random in terms of timing and direction, similar for both conditions. The conditions contained either 1) informative auditory cues, veridically indicating the timing and direction of the upcoming motion, or 2) non-informative cues. Illness ratings were recorded at 1-minute intervals using a 11-point motion sickness scale.

Results: Average illness ratings after exposure were significantly lower for the condition with informative auditory cues, as compared to the condition without informative cues.

Conclusion: Anticipation to unpredictable motion can be facilitated by means of auditory cues, subsequently lowering motion sickness. This knowledge could be used in domains such as that of autonomous vehicles to reduce carsickness, for instance by providing auditory warning on upcoming cornering or decelerations. Interventions of this kind have the benefit that they can be presented even when the occupant is visually engaged (e.g. in a display).

7.1. Introduction

Motion sickness is a state of discomfort that can affect all those with a functioning vestibular system exposed to sufficient provocative motion. Its root cause has been theorized to be a mismatch between sensed and expected motion (Money, 1970; Reason & Brand, 1975). If actual sensory information following motion is sufficiently at odds with the *expected* bodily sensory state, as based on prior experiences, motion sickness occurs (Reason, 1978; Bos & Bles, 1998; Bos et al., 2008; Oman, 1982; Oman, 1990; Bos & Bles, 2002). Furthermore, a plethora of modulating factors are established in the literature, the most well-known effect being the role of visual information. For instance, when below deck in a ship, motion sickness can be significantly worsened due to a visual-vestibular conflict (Bles et al., 1998). In addition, the effect of an individual's capacity to anticipate upcoming motion is known to influence motion sickness (Rolnick & Lubow, 1991). However, even though motion sickness is understood primarily as stemming from an incongruence between sensed and expected motion, the concept of anticipation has only preliminarily studied directly in the literature on motion sickness.

The potentially beneficial effects of the ability to anticipate upcoming motion on subsequent motion sickness have been mentioned in several studies, mainly in the context of carsickness (Griffin & Newman, 2004; Perrin et al., 2013; Wada et al., 2018). However, the number of studies focused primarily on the link between anticipation and motion sickness is limited. In an experiment utilizing a motion platform, Rolnick and Lubow (1991) found that even when two participants were simultaneously exposed to identical motion, the participant in control and thus able to anticipate the motion was significantly less motion sick. A comparable study with exclusively visual motion cues yielded comparable results (Stanney & Hash, 1998). Feenstra and colleagues (2011) found that by showing an artificial "roller coaster like" trajectory offering information on upcoming motion to passive subjects in a 6 DoF motion simulator, motion sickness was reduced by a factor of two. In a previous study (Kuiper et al., 2019) we found that motion composed of events that were presented either at semi-random moments or in semi-random direction were more provocative with respect to sickness as compared to the same events presented at fixed, and thus predictable, moments and directions. To our knowledge, however, it has not been studied whether cues anticipating otherwise unpredictable motion events can reduce sickness in a similar manner.

The latter question is relevant in particular in the domain of transport. In particular, self-driving cars are expected to become commonplace, shifting car occupants from drivers to passengers (Sivak & Schoettle, 2015; Diels & Bos, 2016; Diels et al., 2016), which makes them also more vulnerable to carsickness. Moreover, a benefit of automated vehicles, i.e., the freedom to engage in non-driving activities such as working on a display, can be expected to further exacerbate motion sickness (Cyganski et al., 2015; Probst et al., 1982; Griffin & Newman, 2004; Perrin et al., 2013; Kuiper et al., 2018). Consequently, presenting visual anticipatory cues to reduce sickness may be less practical, raising the question whether, e.g., auditory cues warning for upcoming motion events, such as accelerating or cornering, could be effective as well.

We therefore exposed participants to two conditions of equal motion, i.e. composed of repetitions of an 8-second motion forward-and-backward but at irregular intervals and with uncertainty in direction. In the anticipatory condition, participants received auditory cues one second in advance of the upcoming motion indicating its direction. In the control condition, they received similar auditory cues that were non-informative about timing or direction of the motion. Our hypothesis was that the anticipatory condition with informative cues would lead to less motion sickness as compared to the control condition with non-informative cues.

7.2. Methods

7.2.1. Participants

Approval of the TNO Human Factors institutional Review Board on Experiments with Human Subjects was obtained in accordance with the ethical standards stipulated in the 2013 Declaration of Helsinki. All participants indicated they had no vestibular disorders and were in overall good health. They were instructed to refrain from alcohol the 24 h before the experiment. In advance of the first condition the procedure was explained to participants and they signed an informed consent form. A total of 20 participants participated, 12 males and 8 females. The average age of participants was 39.47 years (*SD* = 12.68).

7.2.2. Motion apparatus and profile

To expose participants to motion we used a 40 m rail track on which a platform (with a cabin) could move forward and backward on a series of 48 wheels. The cabin offered an enclosed environment without visual and airflow cues. Participants sat on a rally car seat that was fixed to the base of the platform, which offered a 5-point safety belt and a headrest. The motion platform was moved forward- and backward by two motors at the far side of the track using synthetic cables. Figure 7.1a and 7.1b respectively show the cabin on the track, and the inside of the cabin.

Figure 7.1a. The 40 m track with the cabin. Only 9 meter peak-to-peak motion was used for the present purpose. **Figure 7.1b.** The cabin interior. The cabin prevented visual and somatosensory (via airflow) information from giving participants information on the occurring motion.

The motion in this experiment was constructed in the exact same manner for the two conditions, 1) Control (C), and 2) Anticipatory (A). Both conditions lasted 15 minutes and consisted of repetitions of raised cosine fore- and backward displacements. Each displacement had a duration of 8 seconds, a total amplitude of 9.0 meters, and a peak acceleration of 2.5 m/s^2. The motion was reversed in direction randomly half of the time, going backwards first, then forwards. Between repetitions, there was a static interval with a duration that varied randomly between 4 and 12 seconds. See Figure 7.3 for a visual representation of the motion profiles over time.

This motion was based on a previous study in which the effects of unpredictable interval duration and motion direction were found to increase motion sickness as compared to a motion profile in which both the interval duration and motion direction were kept constant (Kuiper et al., 2019). We therefore assumed the motion used in this experiment would be sufficiently provocative, and could also potentially be made less so by reducing its unpredictability.

7.2.3. Auditory cues

To facilitate anticipation in the anticipatory condition (A) 1 s in advance of each displacement, a sound clip was played over headphones, veridically communicating “forward” or “backward” (in the native language of the participant). Participants were explained that in this condition always 1 s before motion onset, the auditory cue associated with the direction would be presented. To ensure the control condition (C) was as similar as possible to the anticipatory condition, we also played the sound clips in that condition, but at 2 to 6 s after the actual motion onset, varied randomly. The directionality of the auditory cue was random as well in this condition. We did not explicitly state anything on the relation between the auditory cues and motion sickness to keep participants as naïve as possible.

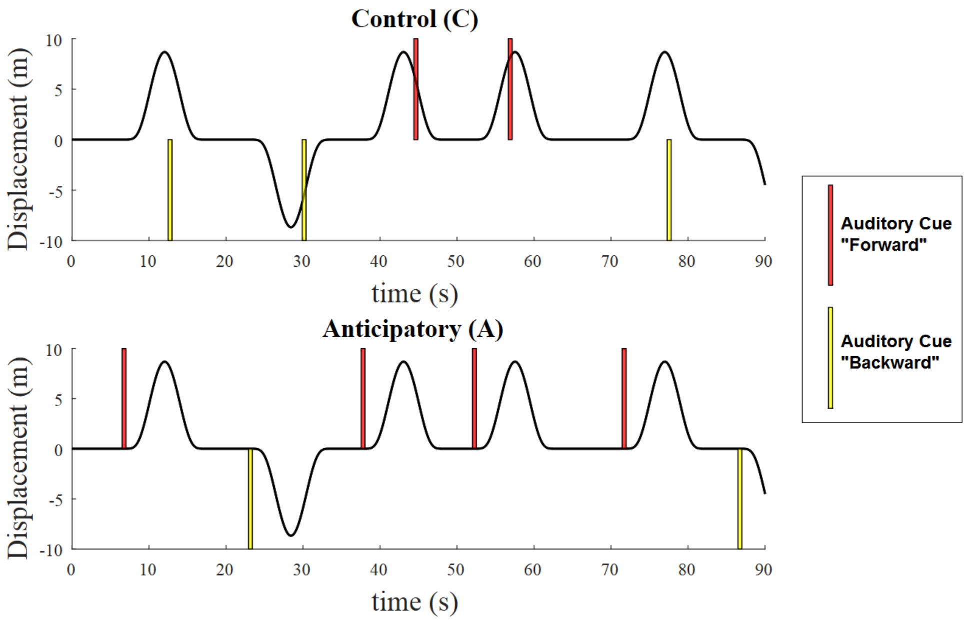

Figure. 7.3. First 90 seconds of the 15 minutes motion profile also showing the timing and directionality of the auditory cues. The motion profile was semi-random in direction and in timing: each condition exposed participant to the same number of displacements in each direction. The auditory cues in the control condition (C) were presented at semi-random timings, 4 to 6 seconds after a motion was already initiated. In the anticipatory condition (A), the auditory cues informed both of timing and of direction, by occurring consistently 1 s before the motion started and with the actual direction of upcoming motion.

7.2.4. MISC

We used an 11-point scale, the *Misery Scale* (MISC) to assess participant motion sickness (Table 7.1, taken from Bos et al., 2005). This scale utilizes the knowledge that motion sickness manifests initially in symptoms such as sweating, yawning, apathy, stomach awareness, and dizziness, which may be followed by nausea, retching and vomiting. Given the single rating, this scale could easily be applied at 1-minute intervals over the course of the experiment. If at any point during a condition nausea occurred (corresponding with a MISC of 6 or higher), the current condition was halted, and that final score was conservatively assumed to stay constant for the remaining minutes.

Table 7.1.
11-point MIsery SCale (MISC) (Bos et al., 2005)

Symptoms		MISC
No problems		0
Some discomfort, but no specific symptoms		1
Dizziness, cold/warm, headache, stomach/throat awareness,	vague	2
sweating, blurred vision, yawning, burping, tiredness,	little	3
salivation, . . . but no nausea	rather	4
	severe	5
Nausea	slight	6
	fairly	7
	severe	8
	(near) retching	9
Vomiting		10

7.2.5. Procedure

Before the experiment, participants filled out the motion sickness susceptibility questionnaire (MSSQ; Golding, 2006), to assess whether our participants were representative of the general population in terms of motion sickness susceptibility. Before the first condition, the procedure was explained and participants signed an informed consent form. Participants were then seated inside the cabin in a comfortable position and were instructed to keep their eyes open and their head in an upright position. Between conditions, participants had a pause of at least one hour to recover from ill effects. The order of conditions was counterbalanced across subjects.

During the experiment, participants were continuously in contact with the experimenter via headphones. In addition, the experimenter could see the participant at all times via a video feed to ensure the participant was safe and remained in a stationary position. The headphone reduced outside noise by 23dB, and we added additional pink noise to mask remaining sound of motors at the far ends of the track, which could have otherwise acted as cues on the motion.

7.3. Results

The average MSSQ scores of participants was 18.49 ± 10.55. This corresponded with the 70th percentile of what would normally be expected in the general population (Golding, 2006).

A repeated measures ANOVA on all MISC values obtained showed a significant effect of condition ($F(1, 19) = 5.933$, $p = .025$, partial $\eta 2 = 0.238$), and of time ($F(15,285) = 38.317$, $p < .001$, partial $\eta 2 = 0.669$) on motion sickness scores.

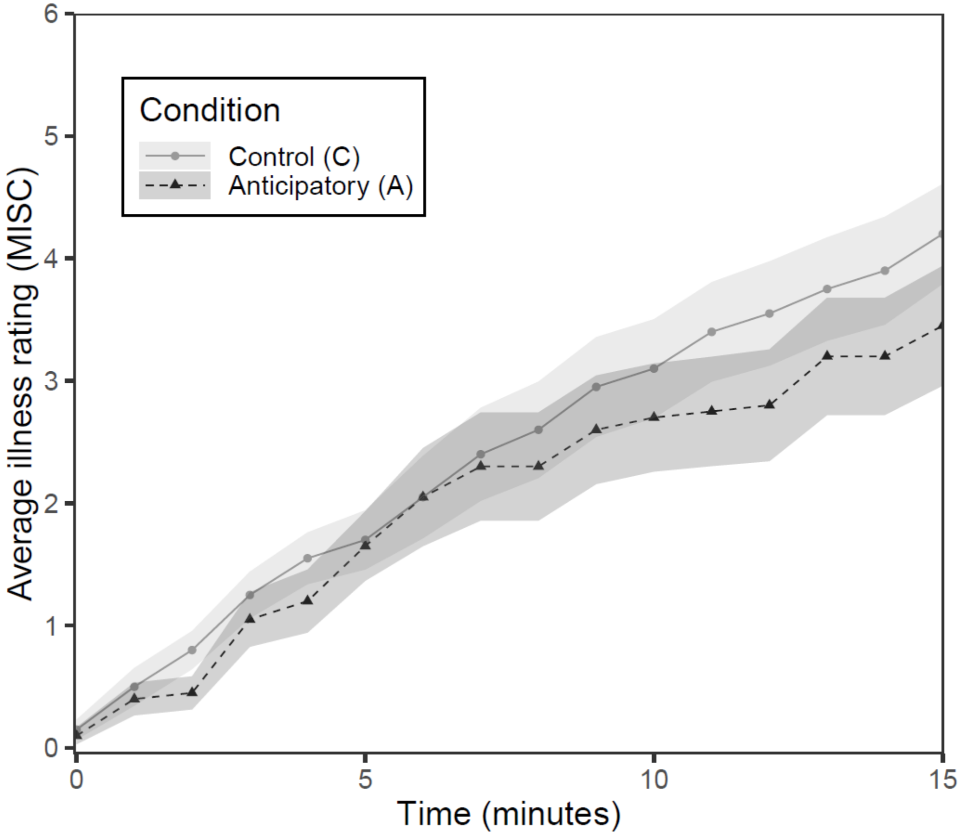

Figure. 7.4. Illness ratings over time for the two conditions. Grey bands depict SEM.

Figure 7.4 shows the average participants' illness ratings over the two 15 minute conditions. For the control condition (C) the average illness rating after 15 minutes was 4.15 (SD = 1.82) while for the anticipatory condition (A) this was 3.45 (SD = 2.19); the effect of the anticipatory cues thus averaged to a difference of 17%.

When only considering illness ratings reported after 15 minutes of exposure to motion, a non-parametric Wilcoxon signed ranked test indicated the baseline condition (Mdn = 5.0) differed from the anticipatory condition (Mdn = 3.0), which was significant ($Z = -2.24$, $p = .025$).

7.4. Discussion

Although the effect of anticipation in relation to motion sickness has been discussed in the literature before (Griffin & Newman, 2004; Rolnick & Lubow, 1991; Feenstra et al., 2011; Perrin et al., 2013), to our knowledge, this study concerned the first within-subjects experiment with an explicit focus on predictability using auditory warnings. After only 15 minutes of exposure to motion that was unpredictable in direction and timing, participants reported significantly lower sickness scores when correct anticipatory auditory information about upcoming events was added (A), as compared to a control condition in which the auditory information was added semi-randomly (C). This finding is of interest from a scientific as well as an applied point of view, which will be discussed further below.

As compared to the effects observed by Feenstra et al. (2011), the effect reported on in the present study was rather small. These authors, however, utilized visual cues in their experiment that were likely to have a bigger effect than auditory cues for two main reasons. First, their visual imagery consisted of continuously moving objects, offering continuous and low level sensory information, therefore potentially having a more pronounced effect as compared to the effect of a single momentary auditory cue, which also might require higher order cognitive processing. The former low level process has previously been referred to as "percipation" (Bos et al., 2008), a process taking place in the order of a second. In this definition, it is distinguished from "anticipation", a process requiring higher order cognitive function, and typically taking place in the order of several (tens of) seconds. Please note that generally the literature, predictive neural processes, i.e. forms of anticipation, are not subdivided in this manner, nor does exploring this division lie in the scope of the present study. Secondly, anticipation was brought about by Feenstra and colleagues using a "roller coaster like" trajectory showing upcoming motion. Moreover, this anticipatory information was continuously updated in their experiment. It seems reasonable to assume that in particular the continuous updating entails a more forceful anticipation than the brief auditory cue as used in our current experiment. Feenstra and colleagues furthermore used motion that varied randomly in all six degrees of motion. The motion studied currently, however, only varied along one axis, in which a single motion event was presented repeatedly. It therefore arguably makes sense to assume that the effect of a countermeasure can be more comprehensive if more degrees of freedom are involved. A third, subordinate point, relates to the knowledge that visual and vestibular cues can interact with respect to postural stability, the latter also being related to motion sickness (Grace et al., 2012; Bos, 2011; Bos et al., 2013). Auditory information is generally unrelated to the process of orientation to gravity, as opposed to visual cues, while orientation has been assumed to be particular interest to motion sickness (Bles et al., 1998). These relationships likely add to the effectiveness of visual cues in mitigating motion sickness.

A further detail concerning the highly diverse 6-dof motion pattern as studied by Feenstra and colleagues (2011), analogous to turbulent aircraft motion, is that it is not representative for car motion and thus carsickness. Vehicle motions generally consist of many horizontal accelerations, and are composed to discrete acceleration, braking and cornering events, rather than a continuously provocative motion pattern. With respect to the interest in self-driving carsickness, in the present study we deliberately opted for distinct motion events, i.e. the periodic 8 s displacement, both because of its similarity to certain car motion events, and also because it could be distinctly preceded by an auditory cue.

Furthermore, two temporal issues can be pointed out that might translate to a potentially even greater effect of anticipation on motion sickness. One issue concerns the limited time of exposure used in the present study, as sickness is known to increase for longer exposure durations (O'Hanlon & McCauley, 1974; ISO 2631, 1997; Bos et al., 2005; Feenstra et al., 2011). It can therefore be expected that a longer period of time would also further increase the difference between conditions observed here. The other issue concerns the 1 second interval between the auditory cue and the actual motion onset, which was chosen somewhat arbitrarily and might not be optimal. A longer period could allow for more time to cognitively process the cue, while, conversely, a shorter time could enable participants to estimate more accurately the time when the motion will occur (Fraisse, 1984). Interestingly, inter-individual differences in perceptual style have been found to influence the ability to accurately time visual motions (Berthleon et al., 1998). Related to these temporal issues, it may be of interest to consider the approximately equal levels of sickness in the two conditions (C and A) during the first ten minutes of motion exposure, only after which a difference becomes evident. A similar pattern can, interestingly, also be seen in two other studies comparing conditions with and without additional information on upcoming motion, one by Griffin & Newman (2004, Figure 7.3) and, the other, again by Feenstra et al., (2011, Figure 7.5a). A possible explanation is that novel types of information, such as the auditory cue as used in our experiment, require some time to be effectively internalized. Due to the study designs, this can however not be concluded, but might be a fruitful topic of further research.

From a theoretical point of view, the current data, though not proving, are in favour of assuming an internal model or neural store allowing the central nervous system (CNS) to predict self-motion based on an "efference copy" of motor commands (Reason & Brand, 1975; Oman, 1982, 1990; Bles et al., 1998; Bos & Bles, 1998, 2002; Bos et al., 2008). Because it is the primary aim of the internal model to make a prediction about self-motion to compensate for neuronal delays, sensor imperfections, and the physically inherent ambiguity between inertial and gravitational accelerations (Bos & Bles, 2002), it naturally follows that this mechanism also accounts for the effect of anticipation. First, and different from the low level process of "percipation" as referred to above, it can be assumed to take time for a novel cue to be internalized within the internal model (or neural store), thus not being effective instantly. Within this internalization period, the CNS will have to reckon the coherence between the novel cue and the actual sickening motion, coherence that typically cannot be concluded on within a second. Only once this coherence is internalized, it can be helpful to make a better prediction about self-motion, thus minimizing the difference between expected and sensed self-motion, and subsequent motion sickness. It is this conflict that has been assumed to be the main cause of motion sickness (Reason & Brand, 1975; Oman, 1982, 1990; Bles et al., 1998). This reasoning can thus well explain the difference observed not only in the experiment discussed here and those by Griffin & Newman (2004) and Feenstra et al. (2011) as mentioned before already. Moreover, all these data suggest an equal time required for this internalization in the order of 10 minutes, which further favours the explanation assuming an internal model.

A possible point of improvement in our study would be to measure to what extent participants in fact attend to the cues. As participants were fairly naïve as how to utilize the cues, potentially some participants 'tuned out', and were forgoing consciously attending to the cues. In addition, an order effect might exist, even though conditions were counterbalanced. Participants either experience, and lean, in their first condition that the cues are either informative, or of no use in anticipation motion. This effect might carry over to the second condition that is experienced.

A separate issue that might be of interest is to compare the findings in the present study to those found in a previous study which employed the same 8 s motion events and the same method of rating motion sickness (Kuiper et al., 2019). In this previous study, three conditions were realized, either unpredictable in direction of the motion events, unpredictable in the pauses between motion events, or unpredictable in neither. The two unpredictable conditions were found to lead to more motion sickness, respectively 3.58 (*SD* = 1.59) for directionally unpredictable, 3.58 (*SD* = 1.65) for the temporally unpredictable, and 2.36 (*SD* = 1.95) for the predictable condition. Notably, the stimulus used in the present study experiment, a combination of the manipulations of the two unpredictable conditions of the previous study, is found to lead to potentially more sickness, namely 4.15 (SD = 1.82). However, as the two studies are based on different populations, a comparison would be underpowered, thus not suitable for further statistical comparison. Nevertheless, an additive effect of detrimental factors might be expected, as based on the literature (Guignard & McCauley, 1982; Feenstra et al., 2011). How such effects interact is not fully known, and necessitates future research.

From an applied point of view, the current results are also of value, in particular for automated driving. As mentioned in the introduction, carsickness has been assumed to become an issue in automated vehicles, more so than it currently is in conventional human-driven vehicles due to more occupants as passengers, and these being visually engaged in non-driving activities. While medicine is effective against carsickness (Lucot, 1998; Zhang et al., 2016), this may not be the preferred option to reduce self-driving carsickness, as they are sedative, affect performance, and have to be taken well in advance. Other approaches, however, are more promising. As we found in the present study, information about upcoming motion events is beneficial, and could be a main reason why currently, in conventional vehicles, drivers are rarely motion sick (Perrin at al., 2013). Employing anticipatory information to warn passengers about upcoming provocative motion in road vehicles might be an elegant but effective way to reduce carsickness. In terms of implementation using warning cues is especially well-suited to autonomous vehicles, since upcoming motion events are generally planned by the vehicle computer seconds before they occur. Auditory or haptic cues may be preferred to visual cues, as in automated driving the use of displays seems to be primarily reserved for entertainment or work related tasks (Steck et al., 2018). Although incorporating visual cues about self-motion to these displays might be considered, this could lead to issues with vection and cybersickness (Keshavarz et al., 2015; Rebenitsch & Owen, 2016), worsening rather than alleviating the situation. An alternative, parallel, approach to reducing carsickness would be to allow for ample vision outside, which is found to be beneficial even when this vision is peripheral (Griffin & Newman, 2004; Kuiper at al., 2018)

In future vehicles, auditory or haptic methods of informing passengers about provocative motion events could provide, relatively non-intrusively, a potential means against carsickness. In aviation, for example, the use of haptic, i.e. vibro-tactile, cues has already show to be of value in aiding spatial orientation, closely related to motion sickness (Van Erp et al., 2006). As autonomous vehicles take shape in our society, many novel human factors questions are bound to arise, such as the impact of rearward facing car seats on passenger well-being (Salter et al., 2019). These novel problems might require novel solutions, combining fundamental theoretical knowledge with human-centered design. While transportation of people by its very nature will always expose individuals to non-natural and potentially provocative physical motion, keeping symptoms of motion sickness to an acceptable minimum might be essential in the coming decades to gain the public's acceptance and facilitate a successful introduction of automated vehicles.

Chapter 8

Summary and Discussion

The road ahead

8.1 Summary

The aim of this thesis was to gain a better understanding of the underlying mechanism and modulating factors that influence carsickness. I first attempted to bring to light the actual scope of the problem of carsickness, and subsequently examined the primary factors in a series of controlled experiments. These not only uncovered both fundamental knowledge on carsickness –specifically in autonomous vehicles–, but also shaped the outline for promising countermeasures. The principal results and implications per chapter are expanded on below. The findings in this thesis build on the existing literature on general motion sickness, but offer important nuances specific to carsickness. The knowledge gained throughout this thesis might potentially have societal relevance, as the expected development of autonomous vehicles in the coming decades demands a novel perspective on what it means to travel by car, and on how to do so comfortably.

First, in **chapter 2** we showed, using an extensive international survey study, that carsickness is still a problem which affects the majority of the population. Our findings replicated effects of age and gender that are well-known in the literature (e.g. Bos et al., 2007; Lawther & Griffin, 1986; Turner & Griffin, 1999a). An additional approach that we used in this survey was to map which factors were reported to be associated with carsickness. The main modulating factors we found were car accelerations, visual activities, and low air quality. Especially visual activities, such as reading or using a smartphone, were reported to lead to carsickness symptoms not only the most frequent, but also with the shortest onset. Notably, occupants of autonomous vehicles might typically be engaged visually, as being able to undertake non-driving tasks is one of such vehicle’s primary benefits (Steck et al., 2017). The use of self-driving cars, we therefore conclude, is expected to increase to occurrence of carsickness. This chapter provided a basis to form subsequent research questions. For instance, the reported modulating factors could further be examined in controlled experiments to empirically verify whether they relate to motion sickness as anecdotally reported. And, conversely, factors reported to worsen carsickness might be shown to also have an antithetical case with a potential to reduce carsickness. For example, reading exacerbates carsickness, but increasing outside vision is beneficial.

In **chapter 3**, we showed in a test track study that increased peripheral vision out of the vehicle can actually reduce motions sickness considerably during provocative motion – a slalom motion in this case. Even when engaged foveally, such as when using a display, peripheral vision is used for our orientation in space and estimation of motion, and has even been argued to be decisively so (Dichgans & Brandt, 1978). Thus, peripheral vision potentially offers relevant sensory information to reduce visual-vestibular incongruence. We indeed found that a head up display, allowing for peripheral vision, led to less carsickness compared to a head down display, offering limited peripheral vision. We theorized that this was the result of, respectively, either reduced or increased sensory conflict. This chapter shows that even under circumstances that are generally quite nauseating, i.e. a combination of limited (foveal) vision and provocative motion, a relatively simple change in the design of the vehicle interior (namely display location) can already have a significant impact on the occurrence of carsickness. Naturally, equipping a vehicle with windows and seating that allows for ample outside vision is an essential prerequisite of design that aims to minimize motion sickness. However, this principle does not appear to be a prominent design consideration found in today’s autonomous vehicle concepts (see e.g. Diels & Bos, 2016; Salter et al., 2019 who discuss this problem). What effect vision out the window and seating could furthermore have on carsickness will be discussed in a later section below.

With the knowledge that a view of the outside world can reduce visual-vestibular conflict, and thereby mitigate motion sickness, the ensuing question might arise what other manipulations could be optimized in vehicles. Assuming display use by the passenger, increasing foveal visual information to reduce the sensory conflict seems incompatible, as the display moves in conjunction with the vehicle. Interestingly, it has been found that an earth-fixed reference frame even when presented using computer visuals can be beneficial (Feenstra et al., 2011). Small scale studies using a ‘see-through’ display during driving seemed promising in lowering carsickness when reading (Miksch et al., 2016). However, as we found in **chapter 4**, artificial visuals suggesting motion are highly complex as they can cause visually induced motion sickness on their own accord, and the mechanism behind this is currently not known precisely. Vection, the visually induced sense of self-motion, is nevertheless assumed to play a principal role in generation of motion (Keshavarz et al., 2015). In a study using constant optic flow, we found that vection is not experienced consistently, and subsequent motion sickness does not relate directly to experienced vection, nor in alterations in vection (as we theorized, similar to Nooij et al., 2017). We conclude that the relation between vection, resulting from artificial visuals suggesting motion, and subsequent motion sickness is not straightforward. In addition to vection, a plethora of aspects typical to artificial images can influence how optic flow can lead to visually induced motion sickness, such as frame information. In brief, using computer visuals to reduce visual-vestibular conflict in vehicles might produce more problems than it solves. These topics will also be further expanded on below.

In contrast to on-road vehicle experiments, driving simulators offer an exceptionally safe research environment. Moreover, they also have the methodological advantage of a high degree of controllability and replicability of both motion and visual cues. In **chapter 5**, we investigated whether simulators are in fact viable research tools for the purpose of studying carsickness. We found that under very restrictive (visual) conditions, simulators with an adequate motion platform might be utilized for this purpose, provided they can recreate the low-frequency accelerations principal to carsickness. The main limiting aspect of a simulator are the artificial visuals, as these can lead to simulator sickness, a phenomenon which has many similarities with the topic discussed in chapter 4. A potential, albeit highly limiting, solution to prevent simulator sickness would be to restrict all vision outside the simulator cabin, thus only using the motion base to recreate the relevant vehicle accelerations that incite motion sickness, analogous to carsickness. Furthermore, we find that another restriction of moving base simulators, the limited displacement range, might be compensated by considering the combination of motion intensity and frequency. As covered in later chapters, using a more unpredictable stimulus might also prove to be a method to maximize provocativeness assuming a limited moving base simulator. If these limitations can be overcome, simulators might prove a crucial research tool for carsickness studies, especially to investigate detrimental effects of illness on task performance with a safety aspect, as motion sickness might decrease driving capacity (Rolnick & Bles, 1989; Bos, 2004). This is especially important in situations of transfer of control, i.e. when the human driver of a self-driving vehicle has to take over control within a limited timeframe (SAE, 2014), where the occupant might have additional difficulty due to carsickness as a result from being a passenger in the period before. The combination of non-driving activities during provocative motion and subsequent safety aspects of driving after transfer of control could safely and accurately be studied using moving base driving simulators. Such scenarios would be challenging to study safely in conventional test vehicles. Therefore, self-driving carsickness has characteristics ideally suited to be studied in simulators.

As outlined in chapter 1, a discrepancy between sensed and expected motion is believed to underlie motion sickness. This discrepancy can be the result of conflicting inter-sensory information, such as described in chapter 3. However, an arguably even more typical aspect facilitating carsickness is the inability to anticipate upcoming motion. Notably, there is comparatively limited literature on the relation between motion sickness and (cognitive) anticipation. The dominant mathematical modelling used to estimate and predict motion sickness even completely omits this aspect (ISO 2631-1, 1997). Therefore, in **Chapter 6**, we performed an experimental study to establish the role that anticipation plays in motion sickness, and the potential magnitude of its effect. We found, using a motion platform (a linear sled), that unpredictable motion, both in timing and direction, was considerably more provocative compared to predictable, repetitive motion. This was so even as the motion in all conditions was completely equal in terms of acceleration intensity and motion frequency. Namely, the motion conditions were composed of exactly the same repeated for-and-backward displacement, varying only by virtue of a semi-random variance in either the length of the pauses between displacements, or in the direction of the displacements. Both unpredictable conditions were equally detrimental to participant well-being. As also found by other authors (Rolnick & Lubow, 1991; Feenstra et al., 2011), anticipation can play a decisive role in the extent to which a motion is provocative. Yet, despite its importance, anticipation often appears to be an afterthought in the discussion on what makes a motion provocative. Rather, the focus in much of the literature is primarily on exclusively the physical motion, occasionally expanded by considering visual factors. Typically, the visual factors are often considered only as being incongruent with the vestibular at a sensory level (e.g. reading when driving causing a visual-vestibular conflict), rather than more broadly considering expectation and anticipation. (Griffin & Newman, 2004; Perrin et al., 2013 being notable exceptions, especially the latter giving credence to the importance of anticipation in carsickness.) I would argue that the cognitive effects of the human individual exposed to motion are equally essential in understanding and preventing motion sickness, and should be given more attention by researchers, engineers, and designers alike. Especially in autonomous vehicles, looking beyond singularly the physical motion can be of considerable importance to realize comfortable and future-proof vehicles.

Building on the knowledge gained on the importance of anticipation in motion sickness, in **chapter 7** we showed, using the same experimental setup, that individuals' anticipation can also be facilitated by auditory cues, and that this can subsequently lower the occurrence of motion sickness. In one condition, sound clips informed participants of the timing and direction of the semi-random upcoming motion. In the control condition, similar auditory cues were present but not informative on direction nor timing of the upcoming motion. Participants reported significantly less illness in the condition that provided them with warning cues that were informative with regards to the imminent motion. To our knowledge, this is the first time it is shown that auditory information can be used and internalized by individuals to anticipate motion in a fashion that reduces how provocative exposure to physical motion is. The effect size that increasing anticipation in this manner had, was not as large as could be expected based on, e.g. chapter 6 and Feenstra et al. (2011). However, this effect could be considerably larger if, for instance, more than one axis of motion is used, as compared to the simple motion in our experiment. Findings of this chapter open the door for further research into countermeasures against motion sickness in autonomous vehicles. Using comparable cues, i.e. simple signals conveying a general direction and/or timing, might actually be excellently suited to the domain of road traffic, as the types of motion scenarios one can expect are generally discrete (e.g. lane changes, cornering, accelerations and decelerating to a halt). These issues and opportunities will be discussed more exhaustively below.

Table 8.1. Overview of the principal findings per chapter

Chapter	Main research question	Principal findings
2	What is the current incidence and severity of carsickness?	Carsickness is an issue still affecting the majority of people
3	Does increased peripheral vision reduce carsickness during display use?	Increased peripheral vision outside via display positioning can reduce carsickness
4	Does vection or do alterations in vection cause visually induced motion sickness (VIMS)?	VIMS occurred but was not predicted by vection, nor alternations in vection
5	Can moving base driving simulators be used to study carsickness?	Under restrictions pertaining to visuals and motion envelope, simulators can be used to study carsickness
6	Is unpredictable motion more sickening than predictable motion?	Unpredictable motion is significantly more provocative compared to predictable motion
7	Can unpredictable motion be made less provocative with auditory cues?	Anticipation to unpredictable motion can be aided by means of auditory cues, subsequently lowering motion sickness

The studies covered in the aforementioned chapters reveal consistently that motion sickness is, foremost, a multifaceted problem. This makes getting a grasp on its underlying mechanism an ongoing scientific endeavour, but also has the practical advantage that a wide range of optimizations exist to potentially reduce carsickness to a minimum. In autonomous vehicles, an abundant variety of not just vehicle motion scenarios (e.g. rural versus city drives), but also occupant activities (e.g. reading versus sleeping) occur. This, in combination with unexplored inter-individual differences, suggest a kaleidoscopic image of potential causes whenever carsickness occurs, but also the associated opportunities to improve it. In the remainder of this discussion I will further explore how the knowledge gained in this thesis might fit in its domain of science, and what it entails specifically concerning autonomous vehicles. First, I will take a closer look at how the findings of chapter 2-7 fit within the theoretical framework we delineated in chapter 1. Subsequently, I will cover the relevance for future research into motion sickness, and potential practical implications for the study and applied design of (autonomous) vehicles.

8.2 Main findings and how they relate to existing theory

The research questions covered in this thesis naturally attempted to isolate singular factors affecting individuals' susceptibility to motion sickness. However, as stated, a recurring theme in the discussions of each separate chapter is that motion sickness is a multifaceted phenomenon. This is the case not just in its genesis, the subsequent influence by modulating factors over time, but even in its manifestation in diverse symptoms. A good illustration of the multifaceted nature of carsickness is that the beneficial role of vision in carsickness generally occurs not strictly via a reduction of sensory conflict (chapter 3), nor of increased anticipation (chapter 6/7), but a combination thereof. While this parallel process is generally acknowledged (e.g. Griffin & Newman, 2004; Perrin et al., 2013), the literature would benefit from additional research to untangle these effects and establish their respective roles in carsickness. Furthermore, differentiating the cognitive versus the sensory mechanisms affecting carsickness is not the only challenge for researchers. Sensory input is never unimodal, i.e. it is always a combination of vestibular, visual, and proprioceptive information. Though even exclusively visual stimuli can be sufficient to incite motion sickness, a vestibular aspect is always at play in the form of visual-vestibular interactions (Bos, 2011) as discussed in chapter 4. That our senses can never be "off", such as the vestibular system due to gravity, makes it virtually impossible to study the effect of a manipulation affecting only a singular sense on motion sickness. As another example, barring direct galvanic or caloric methods (or paralyzing subjects), vestibular stimulation is impossible without also involving proprioceptive information. What the effects of such inevitable coupling of sensory input are should be carefully considered, even in controlled laboratory experiments. For instance, in chapter 5 participants were blindfolded, while in chapter 6 and 7 participants had vision of the interior of the motion device; having the eyes closed generally leads to less illness compared to vision on an observer-fixed interior (Bos et al., 2005; Golding & Kerguelen, 1992). Thus, somewhat higher motion sickness scores can be expected given similar conditions of interior vision, as the latter resembles the adverse situation of having no external view in a vehicle. In particular in real on-road vehicles, a plethora of factors relating to carsickness are at play simultaneously, especially of interest with regard to countermeasures, as will be discussed in more detail in the below.

Relating to the motion sickness theory (MST) and associated model (Oman, 1982, 1990; Bles et al., 1998; see Chapter 1), an important nuance in the discussion surrounding anticipation (as for instance covered in chapters 6 and 7) is to be made. Namely, to differentiate between what could be called conscious "cognitive" anticipation and more rudimentary "sensory" (or "perceptual") anticipation. These two types of prediction stemming from the MST, and assumed to have neural analogues, have also been respectively called *"anticipation"* and *"percipation"* (Bos et al., 2008). This distinction helps us to understand why completely repetitive patterns of motion, such as of a sinusoidal displacement –which are often used both in the literature and in this thesis (most notably O'Hanlon & McCauley, 1974; chapter 3 and 5) – are nevertheless assuredly provocative. This is the case even though for the individual the motion presents no surprises, i.e. there no lack of (cognitive) anticipation. The reason such motion is nonetheless provocative, is because of the latency inherent in our senses and the subsequent mismatch in expected sensory information and actual sensory information, i.e. an error of "*percipation*" (Bos & Bles, 1998). This also explains why a peak frequency exists in terms of provocative motion, generally around 0.2 Hz, as this outcome can consistently be predicted using the model (Bos & Bles, 1998; Bos et al., 2008). Motion that is unpredictable from the perspective of the individual (i.e. lacking "*anticipation*") is an additional modulating factor that can exacerbate motion sickness resulting from the provocative motion, as we found in chapter 6. This effect of added ("cognitive") unpredictability would also explain why combinations of sine wave motion are found to be more provocative than the sum of their parts (Guignard & McCauley, 1982).

In chapter 4, we theorized that it might be alternations in vection, rather than vection *an sich*, that would be predictive of visually induced motion sickness (VIMS), as was also suggested earlier in the literature (Nooij et al., 2017). The rationale for this is that moving at a constant speed does not excite the vestibular organs, i.e. no net force acts during constant speed as stated by Newton's second law – also the reason you can comfortably drink a cup of coffee on an airplane despite the high speed (if there is no turbulence or other erratic accelerations, of course). Therefore, a sensation of constant motion is not at odds with the absence of vestibular inertial cues (i.e., apart from gravity). Throughout the literature it is generally reported that vection is found to be a *necessary*, but not a singularly *sufficient* condition for VIMS (Keshavarz, et al., 2015). It might be (as also suggested by Nooij et al., 2018), that within each individual, an increase in changes in vection do correspond to increased VIMS. However, across individuals, differences in either susceptibility to motion sickness (Golding et al. 2008) or in visual style (Barrett & Thornton, 1968), are too substantial to reveal an effect of changes in vection on illness. The concept of visual style also known as field dependence (Keshavarz et al., 2017), and which influences how vection is experienced. An added difficulty when designing an experiment to study these aspects of vection is that using changes in optic flow with the goal to incite varying levels of vection (e.g. Bonato et al., 2008) make it hard to exclude other factors. One such factor, as we have argued in chapter 4, is that of a rest frame (Prothero, 1998). What is regarded as stationary might be a separate, but crucial, cognitive process wholly distinct from the experience of vection. To reiterate, the effect of artificial visuals suggesting motion on (visually induced) motion sickness is not well-understood, and I would argue that application of artificial visuals suggesting motion should be used with caution in vehicles if carsickness is a concern.

The motion profiles we used in chapter 6 were very similar to the motion profile we used in chapter 7, which allows for some comparison. All the motion stimuli in these chapters were composed of the same 8 second raised cosine motion, i.e. a forward-and-backward displacement, occurring once every 16 seconds. In chapter 6, either the duration of the pauses between displacements, or their direction was semi-randomly varied. In chapter 7, these two manipulations were combined, as both the timing and the direction were semi-randomly varied. Notably, the total displacement, acceleration experienced over time, and thus the root mean square of the motion stimulus were identical for all conditions of both chapters. An initial comparison between illness ratings in chapters 6 and 7 seems to suggest that a combination of unpredictability in direction and in timing (4.15, SD = 1.82) could be more detrimental when compared to those uncertainties isolated (3.58, SD = 1.59 and 3.58, SD = 1.65). As the sample sizes of the two groups are not sufficient for a meaningful between subject comparison, this cannot be concluded as such. However, this is what would be expected given the MST model, as a higher level of uncertainty, and thus a larger discrepancy between sensed and expected motion, would lead to more motion sickness. A highly interesting line of future research would be to examine to what extent different forms of unpredictably are additive in terms of subsequent motion sickness. On a related note, while pure sine wave motion is used in the majority of literature (e.g. ISO 2631-1, 1997), combinations of frequencies might behave differently (Guignard & McCauley, 1982). Cars seldom slalom down the road at a set frequency, and more subtle interactions between coinciding changes in velocity and rotations might have a measurable but currently unknown effect on the magnitude of potential motion sickness. Therefore, more research in how combinations of types of motion interact is highly valuable, specifically for carsickness.

In laboratory studies it has repeatedly been shown that vision on an earth-fixed reference frame, e.g. outside a motion simulator, is beneficial to motion sickness as compared to vision on the interior of the motion device (Rolnick & Bles, 1989; Bos et al., 2005). The most common explanation is the benefit of congruent visual and vestibular information, and likely the principal mechanism at play in those situations. Likewise, in chapter 3, it is argued that this is the reason a display with a high placement is more beneficial, as it reduces visual-vestibular conflict during slalom driving. It should be noted, however, that in contrast to a highly controlled experiment, in on-road tests with real traffic, an individual is exposed to a different environment. Most markedly, it is often far less predictable in terms of upcoming motion as compared to the average lab studies on motion sickness. As we found in chapters 6 and 7, anticipation can be of significant effect on illness. Perhaps even in our controlled slalom experiment as described in chapter 3, the importance of the ability to anticipate upcoming motion might be more substantial than we recognized. I would therefore argue that for on-road studies, researchers should consider to what extent increased vision is beneficial due to a reduced visual-vestibular conflict, or due to an increased ability to anticipate upcoming vehicle motion. Again, a "percipation" and "anticipation" distinction might be made here (see section 8.2).

A commuter in a car can be exposed to a plethora of varying environments, both in terms of physical exposure of motion, seating orientation, but also in terms of visual field effects, anticipation, and other cognitive effects such as distraction or self-fulfilling prophecy when it comes to carsickness (Probst et al., 1982; Vogel et al., 1982; Eden & Zuk, 1995; Turner & Griffin 1999a/b, Griffin & Newman, 2004; Perrin et al., 2013; Bos, 2015; Wada & Yoshida, 2016; Kuiper et al., 2018). The chapters 3, 6 and 7 contribute to the knowledge pool of these factors, while chapter 4 has its relevance in the context of on-board video displays. In the section below I will further explore the potential application of the knowledge gained in this thesis through the lens of actual on-road vehicles and naturalistic scenarios.

8.3 Applying theory to practice to reduce carsickness

The knowledge gained in this thesis on factors of influence on carsickness can relatively easily be translated into practical application in actual (test) vehicles, in the form of active or passive countermeasures against motion sickness. Beforehand, I would like to address that such applications would be geared toward a currently rare state in human-technology interaction, which however could become exceedingly commonplace in transport the near future: an individual who is visually engaged with a display while being exposed to provocative vehicle motion. In current modes of transport, this state is either non-existent, rare, or not yet the subject of study (e.g. the use of laptops or smartphones in busses/coaches has to our knowledge not been the subject of study). In autonomous vehicles, such a state would likely be the norm (Strict et al., 2018). This new form of occupant activity requires, in addition to a theoretical foundation of the workings of carsickness under such conditions, a practical approach to generate non-invasive and human-centric design principles to be able to minimize carsickness. For example, building a car of glass with perfect 360 vision (and thus no on-board displays), while very beneficial in preventing motion sickness, is not a realistic topic of applied research. Compromise is necessary, as the goal of a car manufacturer, and an occupant, is to get from A to B in a fast and productive manner, while also minimizing carsickness; the latter sometimes being at odds with the former. Assuming the novel state of the individual in an autonomous car, an abundance of valuable and legitimate research questions emerge. For a small subset of research questions, hinting at potential implementations to mitigate carsickness, this thesis laid the groundwork (as in chapters 3, 6 and 7), which will be further expanded on below.

Various approaches can be envisaged to attempt to reduce carsickness in a real world scenario, aimed at different factors known to be beneficial. The approaches of most relevance to this thesis are: 1) passively increasing vision outside the vehicle, 2) passively optimizing seating, 3) actively offering an earth-fixed reference frame artificially, 4) actively increasing anticipation via cues, and 5) change vehicle motion or dynamics, the latter being a passive measure from the perspective of the occupant.

The first approach, increasing vision outside, has been shown to be beneficial in chapter 3. A display placed in a way to allow for better vision out-the-window significantly reduced carsickness. While increased vision out-the-window has previously been found to be beneficial (Probst et al., 1982; Griffin & Newman, 2004; Perrin et al., 2013), this benefit was only established for conditions where the participant had an unrestricted gaze, i.e. could have foveal vision outside. To our knowledge, the beneficial effect of exclusively peripheral vision on motion sickness had not been established in the literature before. Given the assumed state of an occupant engaged with a display, our findings in chapter 3 are especially relevant. In addition to placing displays in positions that maximize peripheral vision, the consideration to include windows in autonomous vehicles that allow ample vision, especially forward, would be a good design principle to minimize carsickness.

The second approach, optimizing seating, has not directly been covered in this thesis, yet has been found to have an effect on motion sickness (Mills & Griffin, 2000; Griffin & Newman, 2004). Especially in fully self-driving vehicles without a steering wheel, seating orientation can be reimaged. Backward seating would, however, have a negative effect on carsickness (Turner & Griffin, 1999a; Salter et al., 2019), as a result of having reduced vision outside and on the road ahead. Notably, reclining into a position where the individual lays on one’s back might have interesting consequences. This position, i.e. supine, has been found to reduce the occurrence of motion sickness (Vogel et al., 1982; Golding et al., 1995). This effect has been theorized to be a result of no longer having the need to maintain posture in relation to gravity, thus no longer requiring the neural mechanism as described by the MST (see chapter 1), and hence no cause for motion sickness (Bos & Bles, 2002). If the occupant is sleeping, or having the eyes closed, this is expected to both be additionally beneficial in regards to carsickness (Benson, 2002; Sivak & Schoettle, 2015). A final aspect that should be noted, is that laying supine also has the effect that vision out-the-window is considerably restricted (and even with a sunroof what is seen is less informative of upcoming traffic). Ill-considered seating positioning can mainly be detrimental, since normal forward seated orientation is fairly optimal. However, due to the benefit of laying supine, reclining in an autonomous vehicle might not be so bad.

The third approach, a 'see-through' display as per Miksch et al. (2016), or adding an earth-fixed reference frame using computer visuals in some other fashion, might seem promising at first. After all, it has been shown that artificial computer visuals that offer an earth-fixed reference frame can mitigate motion sickness (Feenstra et al., 2011). It should be noted that Feenstra et al (2011) found an earth-fixed reference frame was beneficial apart from their anticipatory intervention, which also reduced motion sickness. Despite this benefit in a simulator, based on chapter 4 and in general due to the complexity of vection, I would argue that using artificial earth-fixed visuals to attempt to reduce the visual-vestibular conflict aboard a car is unadvised. During travel at constant speed, e.g. on a highway, only negligible accelerations are present and thus also virtually no corresponding vestibular cues. However, a 'see-through' display would show (earth-fixed) objects going by at high speed, presenting the occupant with a strong optic flow stimulus. This could potentially cause (visually induced) motion sickness, as conditions of artificially presented optic flow, leading to vection, are generally also found to also lead to motion sickness. Vection is not experienced in a constant fashion even when optic flow is constant (Keshavarz et al., 2015), as we also find in chapter 4, further complicating predicting how such a display would affect occupants. Additional unknowns are the effect of using 2D versus 3D images, or the effect of using abstract shapes, which give ambiguous information as to what is the actual velocity (as they can be at any distance). Interestingly, problems arising from varying optic flow during travel at constant speed does not seem to arise from real images, as individuals are not generally negatively affected by e.g. occasionally looking out the window of a high-speed train. This might be due to the fact that people are generally good at recognizing velocity when moved in a vehicle – even blindfolded–, possibly due to cognitive factors (Bos et al., 2019). Rather than a 'see-through' display, the next approach I will cover might also be implemented visually (even in the primary display), only in this case by means of increasing anticipation, rather than offering an earth-fixed reference frame.

The fourth approach relates to anticipation as described in chapter 7, where we found that motion sickness can be reduced by warning of upcoming motion events. Increasing the ability to anticipate motion through cues could be done haptically, auditory, or visually, even though the former two would likely be least intrusive for an occupant of a vehicle. As mentioned, vision out-the-window also facilitates anticipation, and reduces potential sensory conflicts. Interestingly, when occupants are warned of a coming deceleration or corning, in addition having a beneficial effect by itself, the occupant could also (shortly) gaze outside, depending on the current visual activity. This unifies several beneficial factors, at a crucial provocative moment, as anticipation is further optimized and veridical visual information congruent with vestibular cues is obtained. Countermeasures that increase anticipation appear highly promising and might be very suited for autonomous vehicles.

The fifth point pertains to vehicle motions. While not the focus of this thesis, the subject warrants a short mention. Automation of transport will require balancing engineering questions and what makes sense from a passenger's perspective. For instance, traveling at the centre of a lane is ideal for lane-keeping from a technical point of view. However, human drivers often deviate from the middle of the lane during a curve, to keep lateral accelerations relatively low (Bellem et al., 2017). An autonomous vehicle driving perfectly optimized from a fuel consumption, safety, and traffic flow perspective does not necessarily constitute a comfortable transit. In addition to keeping accelerations low for the benefit of carsickness, problematic frequencies (e.g. around 0.2 Hz; ISO-2631, 1997), could partially be avoided by automated algorithms.

No approach constitutes a silver bullet, as depending on the road type and individual's susceptibility some carsickness might be inevitable. For example, on a windy road carsickness can be expected due to the highly provocative physical motion, regardless of beneficial factors. Nevertheless, a combination of countermeasures and intelligent principles in design can keep carsickness to a minimum. The difference between vomiting and feeling somewhat queasy is quite large from the passengers' perspective. In fact, often motion sickness goes unrecognized as some of its symptoms such as apathy or tiredness are generally not recognized as such (Lackner, 2014). Also in such cases of mild carsickness, the aforementioned beneficial factors could increase occupant' well-being, without explicit knowledge that discomfort is avoided. Experimental studies with multiple conditions generally show that combining beneficial factors generally has a cumulative effect in reducing motion sickness (e.g. Feenstra et al., 2011). Therefore, a combination, or a subset, of the wide range of possible approaches to attenuate carsickness might prove to be most preferable, depending on the requirements of the occupant of the future autonomous vehicle.

8.4 Future research and the road ahead

Interest in autonomous vehicles has increased exponentially in the past several years (Haboucha et al, 2017). Yet, at what pace and in what form autonomous vehicles will take shape is not entirely clear (Bimbraw, 2015). Companies that develop self-driving cars seem to generally focus on one of two development strategies, either incrementally increasing automated features (SAE level 1-4), or aiming for a vehicle designed for (only) full autonomy (level 5, SAE, 2014). The former can already be seen, as luxury cars gain more and more automated features, which starts with lane keeping assistance, and some already offering automated driving on some roads (Endsley, 2017). These incremental steps in automation go from simple driver-supporting technology, via accumulative developments, all the way to full door-to-door autonomous driving (SAE, 2014). The second approach is to forgo the intermediate steps, and to go straight to completely driverless autonomous vehicles. Such vehicles might have fundamentally different design requirements than conventional vehicles, as, for example, a steering wheel is no longer necessary, and seating that allows for occupants to have a 'social area' might be preferred. This approach would be ideally suited for shuttles or city taxis, where occupants already have different requirements as compared to an individual traveling long distances for work. In current upper segment cars, partial automation is already present. However, legally, technically, and in terms of trust (Choi & Ji, 2015), several strides are yet to be made before autonomous vehicles will be become commonplace. Regardless whether complete and safe autonomy starts in a fancy car or a practical people mover, once a precedent is set, development might accelerate, and the public might quickly gain trust in this novel form of transport.

Comparatively little of the existing literature covers the effect of horizontal motion on comfort in controlled studies. Rather, vertical motion has been predominantly studied in laboratory settings, including some very large-scale studies (e.g. Hemingway, 1942; O'Hanlon & McCauley, 1974). A frequency of 0.2 Hz is generally considered most provocative, higher or lower frequencies being less provocative. As stated in the introduction, there is literature that suggests a similar frequency dependency for horizontal motion and this is generally held as true. For instance, the ISO-2631(1997), based on vertical data, is often applied to horizontal motion (e.g. Griffin & Newman, 2004). However, some findings suggest horizontal frequency dependency might be different (Golding & Markey, 1996; Griffin & Mills, 2002). It might be that while still peaking at 0.2 Hz (Golding at al., 2001), the shape of the distribution is different, e.g. lower and higher horizontal frequencies being relatively more provocative for horizontal motion. An added complexity is that when exposed to horizontal motion, the head more easily tilts in the direction of motion. Subsequently the organs of balance move apart from the body, which has been suggested to have a detrimental effect on motion sickness (Wada et al., 2012). Therefore, a more extensive study into horizontal motion, dominant in car dynamics, seems warranted.

Another promising line of research, which explains in part why individuals react differently to provocative motion, is that of perceptual style. For instance, it could be worthwhile to differentiate between levels of visual dependency across individuals. The manner by which visual information is weighted compared to vestibular information differs among individuals, as can be measured by the rod-and-frame test (Sigman et al., 1979). For example, individuals that are more influenced by visual cues to orient themselves in space are found to be more susceptible to simulator sickness (Barrett & Thornton, 1968). This difference in visual style might also explain why some individuals are more susceptible to some forms of motion sickness than others (e.g. Kennedy et al., 2010; Lackner, 2014). A better understanding of inter-individual differences also has practical applications. Depending on whether individuals are primarily sensitive to provocative motion, visual motion, or a (conflicting) combination thereof, occupants of autonomous vehicles could be advised to refrain from engaging in provocative activities during certain segments of roads.

Another possible explanation for the differences between individuals is that frequency dependency is not necessarily similar for all individuals: some might be more sensitive to either lower or higher frequencies of motion compared to the average peak sensitivity at 0.2 Hz. There is also some evidence that for horizontal motion, frequency dependence is different than for vertical motion, (Golding & Markey, 1996; Griffin & Mills, 2002), notably, even if also peaking at around 0.2 Hz, the function indicating horizontal motion susceptibility might have a differently shaped distribution (Golding at al., 2001). While the exact reasons are not fully known, it can be stated that individuals differ greatly in motion sickness susceptibility, and that this poses both a challenge when designing experimental studies, more so when it comes to predicting the effect a novel motion stimulus will have.

Combing other technological advances with autonomous vehicles could also offer interesting applications and subsequent topics of research. Voice recognition has taken significant steps in the last few years (Hoy, 2018), and will likely be implemented in autonomous vehicles. This would allow for easy occupant feedback ('I'm feeling carsick, please drive more comfortably"). This data could subsequently be used to calibrate a preferred driving style for each occupant, potentially even depending on the detected current activity (e.g. reclined napping is less problematic to carsickness, thus would allow for more sporty driving). In addition, occupant well-being could be automatically assessed by using on-board cameras to recognizing their facial features (Lee et al., 2008). This data could firstly be used to calibrate a preferred driving style for each occupant, potentially even depending on the detected current activity (e.g. napping is less problematic to carsickness, thus would allow for more sporty driving). Secondly, pooling data on well-being and its relation to vehicle dynamics and non-driving activities, for instance from all vehicles of a car manufacturer, could be a highly valuable tools for researchers. This would go far beyond the (extensive) study we did in chapter 2 in terms of scope, also enabling the uncovering of causal relations, and to pinpoint individual differences in susceptibility. A great deal of technologies could potentially be implemented in parallel in autonomous vehicles, however, the future direction of such vehicles and their (interior) specifications is presently uncharted territory and thus hard to predict (Kyriakidis et al., 2017).

Over the coming decades, the fraction of passive transport will likely continue to increase, as technological advances will make autonomous vehicles increasingly safe and efficient. Perhaps in a few centuries, people will look back in amazement on how we let humans control heavy steel motorized contraptions at high speeds through cities and fields, claiming thousands of lives each year. Without a doubt, autonomous vehicles have the potential to offer safer and more efficient roads. To transition to automated traffic, the public will need to accept autonomous vehicles. In addition to crucial aspects such as trust, legislation, and technological requirements, a comfortable ride might be a small, but crucial, piece of the puzzle. Even as we attempt to expand to other planets, motion sickness in the form of space sickness (Clark & Viire, 2017), might be a hurdle. In the end, I believe we will find a way to let technology not only propel us forward into the future, but to do so comfortably.

References

Alexander, S.J., Cotzin, M., Hill, C.J., Ricciuti, E.A., Wendt, G.R. (1945). Weslean University studies of motion sickness: I. The effects of variation of time intervals between accelerations upon sickness rates. *Journal of Psychology* 19:49-62.

Allison, R. S., Howard, I. P., & Zacher, J. E. (1999). Effect of field size, head motion, and rotational velocity on roll vection and illusory self-tilt in a tumbling room. *Perception*, 28(3), 299-306.

Bakwin, H. (1971). Car-sickness in Twins. *Developmental Medicine & Child Neurology*, *13*(3), 310–312.

Balter, S. G. T., Stokroos, R. J., Van De Laar, M. M. M., Hendrice, N., & Kingma, H. (2004). Habituation to galvanic vestibular stimulation for analysis of susceptibility to carsickness. *Acta Oto-Laryngologica*, *124*(6), 690–694.

Bardy, B.G., Warren, W.H., & Kay, B.A. (1999). The role of central and peripheral vision in postural control during walking. *Perception & Psychophysics*, 61(7), 1356–1368.

Barrett, G. V., & Thornton, C. L. (1968). Relationship between perceptual style and simulator sickness. *Journal of Applied Psychology*, *52*(4), 304.

Begg, D. (2014). A 2050 vision for London: what are the implications of driverless transport. Clear Channel. Transport Times, London.

Bellem, H., Klüver, M., Schrauf, M., Schöner, H.-P., Hecht, H., & Krems, J. F. (2017). Can we study autonomous driving comfort in moving-base driving simulators? A validation study. *Human Factors*, 59(3), 442–456.

Benson, A. J. (2002). Motion sickness. In K. B. Pandolf and R. E. Burr (Eds.), *Medical aspects of harsh environments* (pp. 1048-1083). Washington, D.C.: U.S. Department of the Army, Office of the Surgeon General.

Berthelon, C., Mestre, D., Pottier, A., & Pons, R. (1998). Is visual anticipation of collision during self-motion related to perceptual style?. *Acta Psychologica*, *98*(1), 1-16.

Bijveld, M., Bronstein, A. M., Golding, J. F., & Gresty, M. A. (2008). Nauseogenicity of off-vertical axis rotation vs. equivalent visual motion. *Aviation, space, and environmental medicine*, *79*(7), 661-665.

Bimbraw, K. (2015). Autonomous cars: Past, present and future a review of the developments in the last century, the present scenario and the expected future of autonomous vehicle technology. In *2015 12th International Conference on Informatics in Control, Automation and Robotics (ICINCO)*(Vol. 1, pp. 191-198). IEEE.

Bles, W., Bos, J. E., de Graaf, B., Groen, E., & Wertheim, A. H. (1998). Motion sickness: only one provocative conflict? *Brain Research Bulletin*, *47*(5), 481–487.

Bonato, F., Bubka, A., Palmisano, S., Phillip, D., & Moreno, G. (2008). Vection change exacerbates simulator sickness in virtual environments. *Presence: Teleoperators and Virtual Environments*, *17*(3), 283–292.

Bos, J. E., Bles, W., & Groen, E. L. (2008). A theory on visually induced motion sickness. *Displays*, *29*(2), 47–57. https://doi.org/10.1016/j.displa.2007.09.002

Bos J.E., MacKinnon S.N., & Patterson A. (2005). Motion sickness symptoms in a ship motion simulator: effects of inside, outside, and no view. *Aviation Space and Environmental Medicine* 76:1111-1118.

Bos, J. E. (2004). How motions make people sick such that they perform less: a model based approach. *RTO AVT Symposium on" Habitability of Combat and Transport Vehicles: Noise, Vibration and Motion*, *110*, 1–11.

Bos, J. E. (2011). Nuancing the relationship between motion sickness and postural stability. *Displays*, *32*(4), 189–193.

Bos, J. E. (2015). Less sickness with more motion and/or mental distraction. Journal of Vestibular Research, 25(1), 23-33.

Bos, J. E., & Bles, W. (1998). Modelling motion sickness and subjective vertical mismatch detailed for vertical motions. *Brain Research Bulletin*, *47*(5), 537–542.

Bos, J. E., & Bles, W. (2002). Theoretical considerations on canal-otolith interaction and an observer model. *Biological Cybernetics*, *86*(3), 191–207.

Bos, J. E., Bles, W., & Groen, E. L. (2008). A theory on visually induced motion sickness. *Displays*, *29*(2), 47–57.

Bos, J. E., Damala, D., Lewis, C., Ganguly, A., & Turan, O. (2007). Susceptibility to seasickness. *Ergonomics*, *50*(6), 890–901.

Bos, J. E., de Vries, S. C., van Emmerik, M. L., Groen, E. L. (2010). The effect of internal and external fields of view on visually induced motion sickness. *Applied Ergonomics*, 41(4), 516–521.

Bos, J. E., MacKinnon, S. N., & Patterson A (2005). Motion sickness symptoms in a ship motion simulator: effects of inside, outside, and no view. *Aviation Space and Environmental Medicine, 76*, 1111-1118.

Bos, J. E., van den Berg-Kroon, E.M.C., Houben, M.M.J., & Kuiper, O. X. (2019). In-car speed estimations with real, virtual, and no view. *Displays* 58:66-70.

Bos, J.E. (2011). Nuancing the relationship between motion sickness and postural stability. *Displays* 32:189-193.

Bos, J.E. (2004). How motions make people sick such that they perform less: a model based approach. In *RTO AVT Symposium on Habitability of Combat and Transport Vehicles: Noise, Vibration and Motion* (110, pp. 1-11).

Bos, J.E., Ledegang, W.D., Lubeck, A.J.A., & Stins, J.F. (2013). Cineramasickness and postural instability. *Ergonomics* 56:1430-1436.

British Standards Institution. Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock. London, United Kingdom: British Standards Institution; 1987. BS 6841.

Brooks, J. O., Goodenough, R. R., Crisler, M. C., Klein, N. D., Alley, R. L., Koon, B. L., ... & Wills, R. F. (2010). Simulator sickness during driving simulation studies. *Accident analysis & prevention*, *42*(3), 788-796.

Chen, Y.C., Dong, X., Chen, F.C., & Stoffregen, T. A. (2012). Control of a virtual avatar influences postural activity and motion sickness. *Ecological Psychology*, *24*(4), 279–299.

Cheung, B. S. K., Howard, I. P., & Money, K. E. (1991) Visually-induced sickness in normal and bilaterally labyrinthine-defective subjects. *Aviation, Space, and Environmental Medicine, 62*, 527-531.

Cheung, B., & Hofer, K. (2002). Lack of gender difference in motion sickness induced by vestibular Coriolis cross-coupling. *Journal of Vestibular Research, 12,* 191-200.

Cheung, B.S., Howard, I.P., & Money, K.E. (1991). Visually-induced sickness in normal and bilaterally labyrinthine-defective subjects. *Aviat Space Environ Med* 62:527–531

Choi, J. K., & Ji, Y. G. (2015). Investigating the importance of trust on adopting an autonomous vehicle. *International Journal of Human-Computer Interaction*, *31*(10), 692-702.

Clark, J. B., & Viirre, E. (2017). Airsickness and Space Sickness. In *Aeromedical Psychology* (pp. 215-234). CRC Press.

Cyganski, R., Fraedrich, E., & Lenz, B. (2015). Travel-time valuation for automated driving: A use-case-driven study. *Proceedings of the 94th Annual Meeting of the TRB*.

D'Amour, S., Bos, J.E., & Keshavarz, B. (2017). The efficacy of airflow and seat vibration on reducing visually induced motion sickness. *Experimental Brain Research, 235*, 2811-2820.

Dai, M., Raphan, T., Cohen, B. (2007) Labyrinthine lesions and motion sickness susceptibility. Exp Brain Res 178:477–487.

Davis, S., Nesbitt, K., & Nalivaiko, E. (2014). A Systematic Review of Cybersickness. *Proceedings of the 2014 Conference on Interactive Entertainment - IE2014*, 1–9.

Dennison, M. S., Wisti, A. Z., & D'Zmura, M. (2016). Use of physiological signals to predict cybersickness. *Displays*, *44*, 42-52.

Dichgans, J., & Brandt, T. (1978). Visual-vestibular interaction: Effects on self-motion perception and postural control. In Held R., Leibowitz H.W., Teuber H.L. (eds) *Perception* (pp. 755–804), Berlin, Germany: Springer.

Dichgans, J., & Brandt, T. (1973). Optokinetic motion sickness and pseudo-Coriolis effects induced by moving visual stimuli. *Acta Oto-Laryngologica*, *76*(1-6), 339-348.

Diels, C. (2014). Will autonomous vehicles make us sick. In: *Contemporary Ergonomics and Human Factors* pp. 301-307.

Diels, C., & Bos, J.E.,(2015). User interface considerations to prevent self-driving carsickness. In *Adjunct Proceedings of the 7th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 14-19). ACM.

Diels, C., & Bos, J. E. (2016). Self-driving carsickness. *Applied Ergonomics*, *53*, 374–382.

Diels, C., Bos, J.E., Hottelart, K., & Reilhac, P. (2016). Motion Sickness in Automated Vehicles: the Elephant in the Room. In: Gereon Meyer and Sven Beiker (Eds). *Road Vehicle Automation* 3 (pp. 121-129). Switzerland: Springer International Publishing.

Diels, C., & Howarth, P. A. (2011). Visually induced motion sickness: Single-versus dual-axis motion. *Displays*, *32*(4), 175–180.

Diels, C., & Howarth, P. A. (2013). Frequency characteristics of visually induced motion sickness. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *55*(3), 595–604.

Diels, C., Erol, T., Kukova, M., Wasser, J., Cieslak, M., Payre, W., & Bos, J. (2017). Designing for comfort in shared and automated vehicles (SAV): a conceptual framework., *1st International Comfort Congress (ICC)*

Diels, C., Ukai, K., & Howarth, P. A. (2007). Visually induced motion sickness with radial displays: effects of gaze angle and fixation. *Aviation, Space, and Environmental Medicine*, *78*(7), 659–665.

DiZio, P., Ekchian, J., Kaplan, J., Ventura, J., Graves, W., Giovanardi, M., ... & Lackner, J. R. (2018). An active suspension system for mitigating motion sickness and enabling reading in a car. *Aerospace medicine and human performance*, *89*(9), 822-829.

Dobie, T., McBride, D., Dobie, J. T., & May, J. (2001). The effects of age and sex on susceptibility to motion sickness. *Aviation, Space, and Environmental Medicine*, *72*(1), 13–20.

Dong, X., Yoshida, K., & Stoffregen, T. A. (2011). Control of a virtual vehicle influences postural activity and motion sickness. *Journal of Experimental Psychology: Applied*, *17*(2), 128.

Donohew, B. E., & Griffin, M. J. (2004). Motion sickness: effect of the frequency of lateral oscillation. *Aviation, Space, and Environmental Medicine*, *75*(8), 649–656.

Eden, D., & Zuk, Y. (1995). Seasickness as a self-fulfilling prophecy: raising self-efficacy to boost performance at sea. *Journal of Applied Psychology*, *80*(5), 628.

Endsley, M. R. (2017). Autonomous driving systems: A preliminary naturalistic study of the Tesla Model S. *Journal of Cognitive Engineering and Decision Making*, *11*(3), 225-238.

Eurostat (2018) Passenger transport statistics, data extracted in May 2018 from: https://ec.europa.eu/eurostat/statistics-explained/index.php/Passenger_transport_statistics#Modal_split

Evans, J. R., & Mathur, A. (2005). The value of online surveys. *Internet Research*, *15*(2), 195-219.

Eyeson-Annan, M., Peterken, C., Brown, B., & Atchison, D. (1996). Visual and vestibular components of motion sickness. *Aviation, Space, and Environmental Medicine*, *67*(10), 955-962.

Faul, F., Erdfelder, E., Lang, A., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behavior Research Methods, 39(2), 175-191.

Feenstra, P. J., Bos, J. E., & van Gent, R. N. H. W. (2011). A visual display enhancing comfort by counteracting airsickness. *Displays*, *32*(4), 194–200.

Fischer, M. H., & Kornmüller, A. E. (1930). Optokinetically induced motion perception and optokinetic nystagmus. *Journal für Psychologie und Neurologie*, *41*, 273-308.

Förstberg, J. (2000). *Ride comfort and motion sickness in tilting trains* (PhD Thesis). Institutionen för farkostteknik.

Fraisse, P. (1984). Perception and estimation of time. *Annual review of psychology*, *35*(1), 1-37.

Golding JF, & Kerguelen M. (1992). A comparison of the nauseogenic potential of low-frequency vertical versus horizontal linear oscillation. *Aviation, Space, and Environmental Medicine* 63:491-497.

Golding, J. F. (2006). Predicting individual differences in motion sickness susceptibility by questionnaire. *Personality and Individual Differences*, *41*(2), 237–248.

Golding, J. F. (2006a). Predicting individual differences in motion sickness susceptibility by questionnaire. *Personality and Individual Differences*, *41*(2), 237-248.

Golding, J. F. (2006b). Motion sickness susceptibility. *Autonomic Neuroscience*, *129*(1), 67-76.

Golding, J. F., & Gresty, M. A. (2015). Pathophysiology and treatment of motion sickness. *Current opinion in neurology*, *28*(1), 83-88.

Golding, J. F., & Markey, H. M. (1996). Effect of frequency of horizontal linear oscillation on motion sickness and somatogravic illusion. *Aviation, space, and environmental medicine*, *67*(2), 121-126.

Golding, J. F., Arun, S., Wortley, E., Wotton-Hamrioui, K., Cousins, S., & Gresty, M. A. (2009). Off-Vertical Axis Rotation of the Visual Field and Nauseogenicity. *Aviation, Space, and Environmental Medicine*, 80(6), 516–521.

Golding, J. F., Bles, W., Bos, J. E., Haynes, T., & Gresty, M. A. (2003). Motion sickness and tilts of the inertial force environment: active suspension systems vs. active passengers. *Aviation, Space, and Environmental Medicine*, *74*(3), 220-227.

Golding, J. F., Markey, H. M., & Stott, J. R. R. (1995). The effects of motion direction, body axis, and posture on motion sickness induced by low frequency linear oscillation. *Aviation, Space, and Environmental Medicine*. Retrieved from http://psycnet.apa.org/psycinfo/1996-22228-001

Golding, J. F., Mueller, A. G., & Gresty, M. A. (2001). A motion sickness maximum around the 0.2 Hz frequency range of horizontal translational oscillation. *Aviation, Space, and Environmental Medicine*, *72*(3), 188–192.

Grace Gaerlan, M., Alpert, P. T., Cross, C., Louis, M., & Kowalski, S. (2012). Postural balance in young adults: the role of visual, vestibular and somatosensory systems. *Journal of the American Academy of Nurse Practitioners*, *24*(6), 375-381.

Grácio, B. C., Bos, J. E., Van Paassen, M. M., & Mulder, M. (2014). Perceptual scaling of visual and inertial cues. *Experimental Brain Research*, 232(2), 637–646.

Graybiel, A. (1970). Susceptibility to acute motion sickness in blind persons. *Aerospace Medicine*, 41, 650-653.

Greenblatt, J. B., & Shaheen, S. (2015). Automated vehicles, on-demand mobility, and environmental impacts. *Current sustainable/renewable energy reports*, *2*(3), 74-81.

Gresty, M. A., Waters, S., Bray, A., Bunday, K., & Golding, J. F. (2003). Impairment of spatial cognitive function with preservation of verbal performance during spatial disorientation. *Current Biology*, *13*(21), R829–R830.

Griffin, M. J., & Mills, K. L. (2002). Effect of frequency and direction of horizontal oscillation on motion sickness. *Aviation, Space, and Environmental Medicine*, *73*(6), 537–543.

Griffin, M. J., & Newman, M. M. (2004). Visual field effects on motion sickness in cars. *Aviation, Space, and Environmental Medicine*, *75*(9), 739–748.

Griffin, M. J., & Newman, M. M. (2004a). Visual field effects on motion sickness in cars. *Aviation, Space, and Environmental Medicine*, *75*(9), 739–748.

Griffin, M. J., & Newman, M. M. (2004b). An experimental study of low-frequency motion in cars. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, *218*(11), 1231-1238.

Griffin, M. J., & Newman, M. M. (2004b). An experimental study of low-frequency motion in cars. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, *218*(11), 1231–1238.

Guignard, J. C., & McCauley, M. E. (1982). Motion sickness incidence induced by complex periodic waveforms. *Aviation, space, and environmental medicine*, 53(6), 554-563.

Haboucha, C. J., Ishaq, R., & Shiftan, Y. (2017). User preferences regarding autonomous vehicles. *Transportation Research Part C: Emerging Technologies*, *78*, 37-49.

Harris, L. R., Jenkin, M., & Zikovitz, D. C. (2000). Visual and non-visual cues in the perception of linear self motion. *Experimental Brain Research*, *135*(1), 12–21.

Hauser, D. J., & Schwarz, N. (2016). Attentive Turkers: MTurk participants perform better on online attention checks than do subject pool participants. *Behavior Research Methods*, *48*(1), 400-407.

Heberer, T. (2017). *China and Its National Minorities: Autonomy or Assimilation: Autonomy or Assimilation*. Routledge.

Hemingway, A. (1942). Results on 500 swing tests for investigating motion sickness. *AAF School of Aviation Medicine Research Report* (November, 1942) pp. 31-32.

Hemingway, A. (1945). Cardiovascular Changes in Motion Sickness. *Journal of Aviation Medicine* 16:417-421.

Hettinger, L. J. (2002). Illusory self-motion in virtual environments. In *Handbook of virtual environments* (pp. 511-532). CRC Press.

Hettinger, L. J., Berbaum, K. S., Kennedy, R. S., Dunlap, W. P., & Nolan, M. D. (1990). Vection and simulator sickness. *Military Psychology*, *2*(3), 171-181.

Hettinger, L. J., Schmidt, T., Jones, D. L., and Keshavarz, B. (2014). Illusory self-motion in virtual environments. in *Handbook of Virtual Environments: Design, Implementation, and Applications*, eds K. S. Hale and K. M. Stanney (Boca Raton, FL: CRC Press), 435–466.

Hettinger, L., Kennedy, R., & Berbaum, K. (1987). Tracing the etiology of simulator sickness. *Simulators IV*, 105-108.

Hettinger, L.J, Kennedy, R.C., & McCauley, M.E. (1990). Motion and human performance. *Motion and space sickness(A 93-55929 24-52). Boca Raton, FL, CRC Press, Inc., 1990,*, 411-441.

Horn, C. C. (2008). Why is the neurobiology of nausea and vomiting so important?. *Appetite*, *50*(2-3), 430-434.

Howard, I. P., & Childerson, L. (1994). The contribution of motion, the visual frame, and visual polarity to sensations of body tilt. *Perception*, *23*(7), 753–762.

Hoy, M. B. (2018). Alexa, siri, cortana, and more: An introduction to voice assistants. *Medical reference services quarterly*, *37*(1), 81-88.

Hromatka, B. S., Tung, J. Y., Kiefer, A. K., Do, C. B., Hinds, D. A., & Eriksson, N. (2015). Genetic variants associated with motion sickness point to roles for inner ear development, neurological processes and glucose homeostasis. *Human Molecular Genetics*, *24*(9), 2700-2708.

Huppert, D., Benson, J., & Brandt, T. (2017). a historical View of Motion sickness—a Plague at sea and on land, also with Military impact. *Frontiers in Neurology*, *8*, 114.

Irwin, J. A. (1881). THE PATHOLOGY OF SEA-SICKNESS. *The Lancet*, *118*(3039), 907-909.

International Organization for Standardization. *Mechanical vibration and shock: Evaluation of human exposure to whole-body vibration. Part 1: General requirements*. Geneva, Switzerland: International Organization for Standardization; 1997. ISO 2631–1.

ISO 2631-1(1997)E Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration.

ISO14198, 2012. Road vehicles - Ergonomic aspects of transport information and control systems - Calibration tasks for methods which asses driver demand due to the use of in-vehicle systems. ISO/TS 14198:2012(en).

Isu, N., Hasegawa, T., Takeuchi, I., & Morimoto, A. (2014). Quantitative analysis of time-course development of motion sickness caused by in-vehicle video watching. *Displays, 35*, 90-97.

Jaeger, T. F. (2008). Categorical data analysis: Away from ANOVAs (transformation or not) and towards logit mixed models. *Journal of Memory and Language*, *59*(4), 434–446.

Jain, A., Bansal, R., Kumar, A., & Singh, K. D. (2015). A comparative study of visual and auditory reaction times on the basis of gender and physical activity levels of medical first year students. *International Journal of Applied and Basic Medical Research*, *5*(2), 124.

James, W. (1883). The sense of dizziness in deaf-mutes. *American Annals of the Deaf and Dumb*, *28*(2), 102-117.

Ji, J. T. T., So, R. H. Y., & Cheung, R. T. F. (2009). Isolating the Effects of Vection and Optokinetic Nystagmus on Optokinetic Rotation-Induced Motion Sickness. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *51*(5), 739–751.

Johnson, W. H., Sunahara, F. A., & Landolt, J. P. (1999). Importance of the vestibular system in visually induced nausea and self-vection. *Journal of Vestibular Research*, *9*(2), 83-87.

Kamiji, N., Kurata, Y., Wada, T., & Doi, S. ’ichi. (2007). Modeling and validation of carsickness mechanism. *SICE, 2007 Annual Conference*, 1138–1143.

Karjanto, J., Yusof, N., Wang. C,, Terken. J,, Delbressine. F,, Rauterberg. M, (2018). The effect of peripheral visual feedforward system in enhancing situation awareness and mitigating motion sickness in fully automated driving. *Transportation Research Part F: Traffic Psychology and Behaviour* 58:678-692.

Kato, K., & Kitazaki, S. (2006). A Study for Understanding Carsickness Based on the Sensory Conflict Theory. *SAE Technical Papers*, 4:01-0096.

Kato, K., & Kitazaki, S. (2008). Improvement of ease of viewing images on an in-vehicle display and reduction of carsickness (No. 2008-01-0565). SAE Technical Paper.

Kennedy, R. S., & Fowlkes, J. E. (1992). Simulator sickness is polygenic and polysymptomatic: Implications for research. *The International Journal of Aviation Psychology*, 2(1), 23-38.

Kennedy, R. S., Drexler, J., & Kennedy, R. C. (2010). Research in visually induced motion sickness. *Applied Ergonomics*, *41*(4), 494–503.

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology*, *3*(3), 203–220.

Keshavarz, B., & Hecht, H. (2014). Pleasant music as a countermeasure against visually induced motion sickness. *Applied Ergonomics, 45*(3), 521-527.

Keshavarz, B., Hecht, H., & Lawson, B. D. (2014). Visually induced motion sickness: causes, characteristics, and countermeasures. In *Handbook of virtual environments* (pp. 652-703). CRC Press.

Keshavarz, B., Riecke, B. E., Hettinger, L. J., & Campos, J. L. (2015). Vection and visually induced motion sickness: how are they related? *Frontiers in Psychology*, *6*, *472.*

Keshavarz, B., Riecke, B. E., Hettinger, L. J., & Campos, J. L. (2015). Vection and visually induced motion sickness: how are they related? *Frontiers in Psychology*, *6*, 472.

Keshavarz, B., Speck, M., Haycock, B., & Berti, S. (2017). Effect of different display types on vection and its interaction with motion direction and field dependence. *I-Perception*, *8*(3), 2041669517707768.

Keshavarz, B., Stelzmann, D., Paillard, A., & Hecht, H. (2015). Visually induced motion sickness can be alleviated by pleasant odors. *Experimental Brain Research,* 233(5), 1353–1364.

Khan, S., & Chang, R. (2013). Anatomy of the vestibular system: a review. *NeuroRehabilitation*, *32*(3), 437-443.

Klosterhalfen, S., Kellermann, S., Pan, F., Stockhorst, U., Hall, G., & Enck, P. (2005). Effects of ethnicity and gender on motion sickness susceptibility. *Aviation, Space, and Environmental Medicine*, *76*(11), 1051-1057.

Kristensen, M., & Hansen, T. (2004). Statistical analyses of repeated measures in physiological research: a tutorial. *Advances in Physiology Education*, *28*(1), 2–14.

Kuiper, O. X., Bos, J. E., & Diels, C. (2018). Looking forward: In-vehicle auxiliary display positioning affects carsickness. *Applied Ergonomics*, *68*, 169–175.

Kuiper, O. X., Bos, J. E., & Diels, C. (2019). Vection does not necessitate visually induced motion sickness. *Displays*, *58*, 82–87.

Kuiper, O. X., Bos, J. E., Diels, C., & Cammaerts, K. (2019). Moving base driving simulators' potential for carsickness research. *Applied ergonomics*, *81*, 102889.

Kuiper, O. X, Bos, J. E., Schmidt, E. S., Diels, C., Wolter, S. (2019). Knowing What's Coming: Unpredictable Motion Causes More Motion Sickness. Manuscript accepted for publication. DOI: 10.1177/0018720819876139.

Kuo, A. D. (2002). The relative roles of feedforward and feedback in the control of rhythmic movements. *Motor control*, *6*(2), 129-145.

Kyriakidis, M., de Winter, J. C. F., Stanton, N., Bellet, T., van Arem, B., Brookhuis, K., … Happee, R. (2017). A human factors perspective on automated driving. *Theoretical Issues in Ergonomics Science*, 1–27.

Lackner, J. R. (2014). Motion sickness: more than nausea and vomiting. *Experimental Brain Research*, *232*(8), 2493–2510.

Lampinen M (2017). AVs and motion sickness - Solve motion sickness to win at autonomous driving. *Automotive Megatrends Magazine* Q3:23-25.

Lawther, A., & Griffin, M. J. (1986). The motion of a ship at sea and the consequent motion sickness amongst passengers. *Ergonomics*, 29(4), 535–552.

Lawther, A., & Griffin, M. J. (1987). Prediction of the incidence of motion sickness from the magnitude, frequency, and duration of vertical oscillation. *The Journal of the Acoustical Society of America*, 82(3), 957–966.

Lawther, A., & Griffin, M. J. (1988). A survey of the occurrence of motion sickness amongst passengers at sea. *Aviation, Space, and Environmental Medicine*, *59*(5), 399–406.

Le Vine, S., Zolfaghari, A., & Polak, J. (2015). Autonomous cars: the tension between occupant experience and intersection capacity. *Transportation Research Part C: Emerging Technologies*, *52*, 1–14.

Lee, B., Chun, J., & Park, P. (2008). Classification of facial expression using svm for emotion care service system. In *2008 Ninth ACIS International Conference on Software Engineering, Artificial Intelligence, Networking, and Parallel/Distributed Computing* (pp. 8-12). IEEE.

Lin, J.W., Duh, H. B.L., Parker, D. E., Abi-Rached, H., & Furness, T. A. (2002). Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment. In Virtual Reality, 2002. *Proceedings. IEEE* (pp. 164–171). IEEE.

Litman, T. (2017). *Autonomous vehicle implementation predictions*. Victoria Transport Policy Institute Victoria, Canada.

Lubeck, A. J., Bos, J. E., & Stins, J. F. (2015). Interaction between depth order and density affects vection and postural sway. *PloS One*, *10*(12), e0144034.

Lucot, J.B. (1998). Pharmacology of motion sickness. *Journal of Vestibular Research* 8:61-66.

Manning, G. W., & Stewart, W. G. (1949). Effect of body position on incidence of motion sickness. *Journal of Applied Physiology*, *1*(9), 619–628.

Mayne, R. (1974). A systems concept of the vestibular organs. In *Vestibular system part 2: psychophysics, applied aspects and general interpretations* (pp. 493-580). Springer, Berlin, Heidelberg.

McCauley, M.E., Royal, J.W., Wylie, C.D., O'Hanlon, J.F., & Mackie, R.R. (1976). Motion sickness incidence: exploratory studies of habituation, pitch and roll, and the refinement of a mathematical model. Technical Report 1733-2, Goleta, CA: Human Factors Research Inc.

McGill, M., Ng, A., Brewster, S. (2017). I am the passenger: How visual motion cues can influence sickness for in-car VR. *CHI Conference on Human Factors in Computing Systems*, Denver, CO, USA, 6-11 May:5655-5668.

McKenzie, B. (2015). Who Drives to Work? Commuting by Automobile in the United States: 2013. *American Community Survey Reports*. Washington, DC: US Bureau of the Census.

Miksch, M., Steiner, M., Miksch, M., & Meschtscherjakov, A. (2016). Motion Sickness Prevention System (MSPS): Reading Between the Lines. In *Adjunct Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 147-152). ACM.

Miller, E.F., & Graybiel, A. (1972). Semicircular canals as a primary etiological factor in motion sickness. Aerosp Med 43:1065–1074

Mills, K. L., & Griffin, M. J. (2000). Effect of seating, vision and direction of horizontal oscillation on motion sickness. *Aviation, Space, and Environmental Medicine*, *71*(10), 996–1002.

Min, B.C., Chung, S.C., Min, Y.K., & Sakamoto, K. (2004). Psychophysiological evaluation of simulator sickness evoked by a graphic simulator. *Applied Ergonomics*, *35*(6), 549–556.

Monen, J., & Brenner, E. (1994). Detecting changes in one's own velocity from the optic flow. *Perception*, *23*(6), 681–690.

Money, K. E. (1970). Motion sickness. *Physiological Reviews*, *50*(1), 1–39.

Moss, J. D., & Muth, E. R. (2011). Characteristics of head-mounted displays and their effects on simulator sickness. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *53*(3), 308–319.

Mourant, R. R., & Thattacherry, T. R. (2000). Simulator sickness in a virtual environments driving simulator. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 44, No. 5, pp. 534-537). Sage CA: Los Angeles, CA: SAGE Publications.

Nooij, S. A. E., Pretto, P., & Bülthoff, H. H. (2018). More vection means more velocity storage activity: a factor in visually induced motion sickness? *Experimental Brain Research*.

Nooij, S. A. E., Pretto, P., Oberfeld, D., Hecht, H., & Bülthoff, H. H. (2017). Vection is the main contributor to motion sickness induced by visual yaw rotation: Implications for conflict and eye movement theories. *PLOS ONE*, *12*(4), e0175305.

Nulty, D. D. (2008). The adequacy of response rates to online and paper surveys: what can be done? *Assessment & Evaluation in Higher Education*, *33*(3), 301-314.

O'Hanlon, J. F., & McCauley, M. E. (1974). Motion sickness incidence as a function of the frequency and acceleration of vertical sinusoidal motion. *Aerosp Med*; 45, 366 –9.

O'Hanlon, J. F., & McCauley, M. E. (1974). Motion sickness incidence as a function of the frequency and acceleration of vertical sinusoidal motion. *Aerospace Medicine*, 45, 366-369.

Oman, C. M. (1982). A heuristic mathematical model for the dynamics of sensory conflict and motion sickness. *Acta Oto-Laryngologica*, *94*(sup392), 4–44.

Oman, C. M. (1990). Motion sickness: a synthesis and evaluation of the sensory conflict theory. *Canadian Journal of Physiology and Pharmacology*, *68*(2), 294–303.

Paillard, A. C., Lamôré, M., Etard, O., Millot, J.-L., Jacquot, L., Denise, P., & Quarck, G. (2014). Is there a relationship between odors and motion sickness? *Neuroscience Letters, 566*, 326-330.

Paillard, A. C., Quarck, G., Paolino, F., Denise, P., Paolino, M., Golding, J. F., & Ghulyan-Bedikian, V. (2013). Motion sickness susceptibility in healthy subjects and vestibular patients: effects of gender, age and trait-anxiety. *Journal of Vestibular Research*, *23*(4, 5), 203-209.

Paillard, A., Jacquot, L., Millot, J.L. (2011) Olfactory perception and motion sickness,Chem. Senses 36 (2011) E35.

Palmisano, S., A., Bonato, F., Bubka, A., & Folder, J. (2007). Vertical display oscillation effects on forward vection and simulator sickness. *Aviation, Space, and Environmental Medicine*, *78*(10), 951–956.

Palmisano, S., Allison, R. S., Schira, M. M., & Barry, R. J. (2015). Future challenges for vection research: definitions, functional significance, measures, and neural bases. *Frontiers in Psychology*, *6*, 193.

Perrin, P., Lion, A., Bosser, G., Gauchard, G., & Meistelman, C. (2013). Motion Sickness in Rally Car Co-Drivers. *Aviation, Space, and Environmental Medicine*, *84*(5), 473–477.

Persson, R. (2008). *Tilting trains: technology, benefits and motion sickness.* PhD Thesis. Royal Institute of Technology (KTH).

Plunkett, J. W. (Ed.). (2007). *Plunkett's Automobile Industry Almanac: Automobile, Truck and Specialty Vehicle Industry Market Research, Statistics, Trends & Leading Companies*. Plunkett Research, Ltd..

Probst, T., Krafczyk, S., Büchele, W., & Brandt, T. (1982). Visuelle prävention der Bewegungskrankheit im Auto. *Archiv Für Psychiatrie Und Nervenkrankheiten*, *231*(5), 409–421.

Prothero, J. D. (1998). *The role of rest frames in vection, presence and motion sickness*. Doctoral dissertation. University of Washington. Seattle. USA.

Prothero, J. D., Draper, M. H., Furness 3rd, T. A., Parker, D. E., & Wells, M. J. (1999). The use of an independent visual background to reduce simulator side-effects. *Aviation, Space, and Environmental Medicine*, *70*(3 Pt 1), 277–283.

R Core Team, (2017). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Reason, J. T. (1978). Motion sickness adaptation: a neural mismatch model. *Journal of the Royal Society of Medicine*, *71*(11), 819-829.

Reason, J. T., & Brand, J. J. (1975). *Motion Sickness.* Academic Press, London, New York, San Francisco.

Rebenitsch, L., & Owen, C. (2016). Review on cybersickness in applications and visual displays. *Virtual Reality*, *20*(2), 101–125. https://doi.org/10.1007/s10055-016-0285-9

Reed, N., Diels, C., & Parkes, A. M. (2007). Simulator sickness management: Enhanced familiarisation and screening processes. In *Proceedings of the First International Symposium on Visually Induced Motion Sickness, Fatigue, and Photosensitive Epileptic Seizures* (VIMS2007) (pp. 156–162). VIMS Hong Kong, PRC.

Reilhac, P., Millett, N., & Hottelart, K. (2016). Shifting Paradigms and Conceptual Frameworks for Automated Driving. In *Road Vehicle Automation 3* (pp. 73-89). Springer International Publishing.

Riccio, G. E., & Stoffregen, T. A. (1991). An ecological theory of motion sickness and postural instability. *Ecological Psychology*, *3*(3), 195–240.

Rolnick, A. (1986). Exploring the active-passive distinction in movement control remote control of passive rotation can reduce vestibular after-effects and motion sickness. In *Proceedings of the 8th International symposium on posturography*.

Rolnick, A., & Bles, W. (1989). Performance and well-being under tilting conditions: The effects of visual reference and artificial horizon. *Aviation, Space, and Environmental Medicine*, *60*, 779–785.

Rolnick, A., & Lubow, R. E. (1991). Why is the driver rarely motion sick? The role of controllability in motion sickness. *Ergonomics*, *34*(7), 867–879.

SAE, (2014). Taxonomy and Definitions for Terms Related to on-road Motor Vehicle Automated Driving Systems, J3016.

Salter, S., Diels, C, Herropts, P., Kanarachos, S., & Thake, D. (2019). Motion sickness in automated vehicles with forward and rearward facing seating orientations. Applied Ergonomics, 78, 54-61.

Sawabe, T., Kanbara, M., Hagita, N. (2017). Diminished reality for acceleration stimulus: motion sickness reduction with vectionn for autonomous driving. *Proc. IEEE Conference on Virtual Reality and 3D User Interfaces*, Los Angeles, CA, USA, 18-22 March:277-278.

Schoettle, B., & Sivak, M. (2009). In-Vehicle Video and Motion Sickness. UMTRI Report No. UMTRI-2009-6. University of Michigan Transportation Research Institute, Ann Arbor.

Seno, T., Sawai, K., Kanaya, H., Wakebe, T., Ogawa, M., Fujii, Y., & Palmisano, S. (2017). The Oscillating Potential Model of Visually Induced Vection. *I-Perception*, *8*(6), 2041669517742176.

Sharma, K. (1980). Susceptibility to Motion Sickness. *Acta Geneticae Medicae et Gemellologiae: Twin Research*, *29*(02), 157–162.

Sigman, E., Goodenough, D. R., & Flannagan, M. (1979). Instructions, illusory self-tilt and the rod-and-frame test. *The Quarterly Journal of Experimental Psychology*, *31*(1), 155-165.

Sivak, M., Schoettle, B. (2015). Motion sickness in self-driving vehicles. *Report of the University of Michigan, Transport Research Institute*, Ann Arbor, Michigan, U.S.A. UMTRI-2015-12:1-13.

Smart Jr, L. J., Stoffregen, T. A., & Bardy, B. G. (2002). Visually induced motion sickness predicted by postural instability. *Human Factors*, *44*(3), 451–465.

Smyth, J., Jennings P., Mouzakitis, A., Birrell, S. (2018). Too sickn to drive: How motion sickness sevirity impacts human performance. *IEEE Int. Conf. on Intelligent Transportation Systems* (ITSC).

So, R. H. Y., & Ujike, H. (2010). Visually induced motion sickness, visual stress and photosensitive epileptic seizures: What do they have in common? – Preface to the special issue. *Applied Ergonomics*, 41(4), 491–493.

Stanney, K. M., & Hash, P. (1998). Locus of user-initiated control in virtual environments: Influences on cybersickness. *Presence*, *7*(5), 447–459.

Stanney, K. M., & Kennedy, R. S. (1997). The psychometrics of cybersickness. *Communications of the ACM*, *40*(8), 66-68.

Stanney, K. M., Kennedy, R. S., & Drexler, J. M. (1997). Cybersickness is not simulator sickness. In *Proceedings of the Human Factors and Ergonomics Society annual meeting* (Vol. 41, pp. 1138–1142). SAGE Publications Sage CA: Los Angeles, CA.

Steck, F., Kolarova, V., Bahamonde-Birke, F., Trommer, S., & Lenz, B. (2018). How autonomous driving may affect the value of travel time savings for commuting. *Transportation Research Record: Journal of the Transportation Research Board*, 0361198118757980.

Stern, R. M., Hu, S., Anderson, R. B., Leibowitz, H. W., & Koch, K. L. (1990). The effects of fixation and restricted visual field on vection-induced motion sickness. *Aviation, Space, and Environmental Medicine*, 61(8), 712-715.

Stoffregen, T. A., & Riccio, G. E. (1991). An ecological critique of the sensory conflict theory of motion sickness. *Ecological Psychology*, *3*(3), 159–194.

Tal, D., Gonen, A., Wiener, G., Bar, R., Gil, A., Nachum, Z., & Shupak, A. (2012). Artificial horizon effects on motion sickness and performance. *Otology & Neurotology*, *33*(5), 878–885.

Turan, O., Sebastiani, L., Ganguly, A., Bos, J., Lewis, C. (2005). New findings regarding effects of ship motions on human comfort and the way forward. *International Workshop on Human Factors Impact on Ship Design*, Genova, Italy, 6 October.

Turner, M., & Griffin, M. J. (1999a). Motion sickness in public road transport: the effect of driver, route and vehicle. *Ergonomics, 42*(12), 1646-1664.

Turner, M., & Griffin, M. J. (1999b). Motion sickness in public road transport: passenger behaviour and susceptibility. *Ergonomics*, *42*(3), 444–461.

Van Emmerik, M.L., De Vries, S.C., & Bos, J.E. (2011). Internal and external fields of view affect cybersickness. *Displays* 32:169-174.

Van Erp, J. B., Groen, E. L., Bos, J. E., & Van Veen, H. A. (2006). A tactile cockpit instrument supports the control of self-motion during spatial disorientation. *Human factors*, *48*(2), 219-228.

Vlakveld, W.P. (2016). Transition of control in highly automated vehicles: a literature review. The Hague, SWOV Institute for Road Safety Research.

Vogel, H., Kohlhaas, R., & von Baumgarten, R. J. (1982). Dependence of motion sickness in automobiles on the direction of linear acceleration. *European Journal of Applied Physiology and Occupational Physiology*, *48*(3), 399–405.

Wada, T. (2016). *Motion sickness in automated vehicles.* Presented at the International Symposium on Advanced Vehicle Control, September 2016, Munich.

Wada, T., & Yoshida, K. (2016). Effect of passengers' active head tilt and opening/closure of eyes on motion sickness in lateral acceleration environment of cars. *Ergonomics*, *59*(8), 1050–1059.

Wada, T., Fujisawa, S., & Doi, S. (2018). Analysis of driver's head tilt using a mathematical model of motion sickness. *International Journal of Industrial Ergonomics*, *63*, 89–97.

Wada, T., Konno, H., Fujisawa, S., & Doi, S. (2012). Can passengers' active head tilt decrease the severity of carsickness? Effect of head tilt on severity of motion sickness in a lateral acceleration environment. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *54*(2), 226–234.

Warren, W.H., & Kurtz, K.J. (1992). The role of central and peripheral vision in perceiving the direction of self-motion. *Perception & Psychophysics*, 51(5), 443–454.

Webb, N. A., & Griffin, M. J. (2002). Optokinetic stimuli: motion sickness, visual acuity, and eye movements. *Aviation, Space, and Environmental Medicine*, *73*(4), 351–358.

Webb, N. A., & Griffin, M. J. (2003). Eye movement, vection, and motion sickness with foveal and peripheral vision. *Aviation, Space, and Environmental Medicine*, *74*(6), 622–625.

World Medical Association. (2013). WMA Declaration of Helsinki-Ethical principles for medical research involving human subjects.

Wright, K. B. (2005). Researching Internet-based populations: Advantages and disadvantages of online survey research, online questionnaire authoring software packages, and web survey services. *Journal of Computer-mediated Communication, 10*(3), JCMC1034.

Zakharenko, R. (2016). Self-driving cars will change cities. *Regional Science and Urban Economics*, *61*, 26-37.

Zhang, L.L., Wang, J.Q., Qi, R.R., Pan, L.L., Li, M., & Cai, Y.L. (2016). Motion sickness: current knowledge and recent advance. *CNS Neuroscience and Therapeutics* 22:15-24.

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